US005359447A

# United States Patent [19]

Hahn et al.

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[45] Date of Patent: Oct. 25, 1994

[54] **OPTICAL COMMUNICATION WITH VERTICAL-CAVITY SURFACE-EMITTING LASER OPERATING IN MULTIPLE TRANSVERSE MODES**

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[73] Assignee: **Hewlett-Packard Company**, Palo Alto, Calif.

[21] Appl. No.: **83,739**

[22] Filed: **Jun. 25, 1993**

[51] Int. Cl.[5] .............................................. **H04B 10/00**

[52] U.S. Cl. .................................... **359/154**; 359/173; 372/38

[58] **Field of Search** ............... 359/154, 161, 173, 180, 359/188, 195; 372/38, 45

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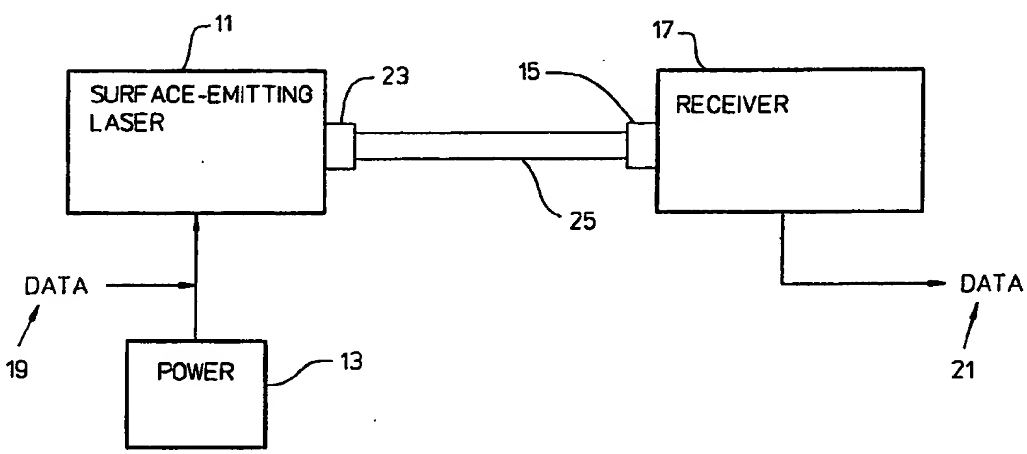
*Primary Examiner*—Richard E. Chilcot, Jr.
*Assistant Examiner*—Kinfe-Michael Negash

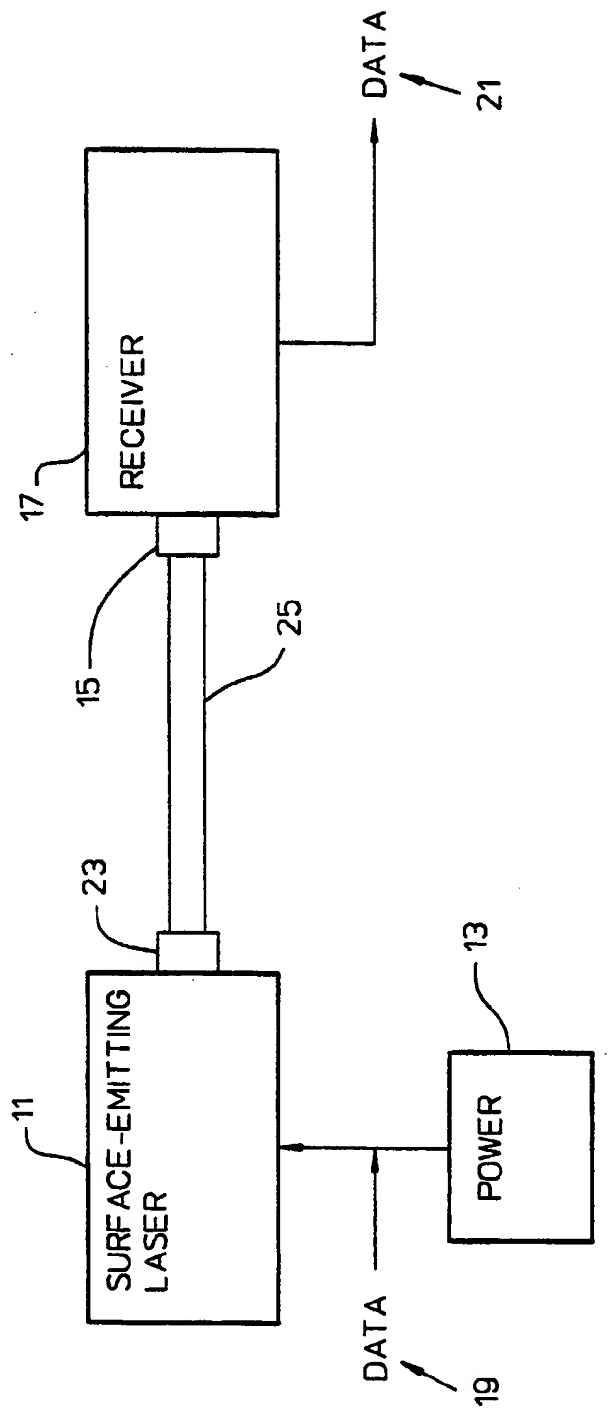
[57] **ABSTRACT**

An optical communication system using a relatively large-area vertical-cavity surface-emitting laser. The laser has an opening larger than about eight micrometers and is coupled to a multimode optical fiber. The laser is driven into multiple transverse mode operation, which includes multiple filamentation as well as operation in a single cavity.

**6 Claims, 2 Drawing Sheets**

Cl 16

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21
RECEIVER
17
15
25
23
13
SURFACE-EMITTING LASER
11
POWER
DATA
19

FIG. 1

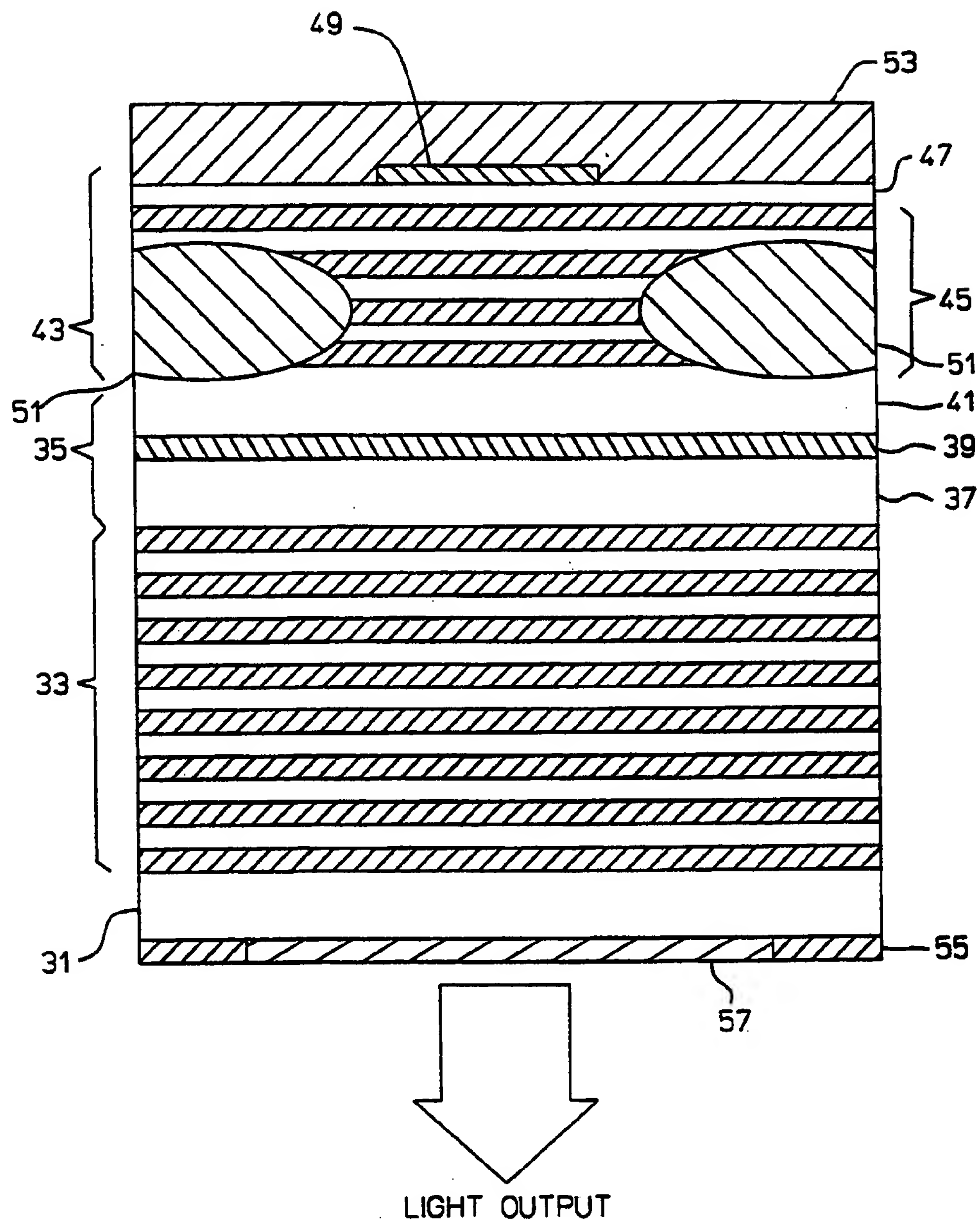


FIG. 2

# OPTICAL COMMUNICATION WITH VERTICAL-CAVITY SURFACE-EMITTING LASER OPERATING IN MULTIPLE TRANSVERSE MODES

## BACKGROUND OF THE INVENTION

The present invention relates generally to optical transmission of signals and more particularly to an optical communication network of the kind having a multimode optical fiber that receives a multiple mode beam of light from a vertical-cavity, surface-emitting laser being operated in multiple modes or multiple filamentation.

Optical communication systems are used to carry information from one location to another. One of the advantages of optical systems is that they have extremely wide bandwidths. This means that optical systems can carry much more information than can other kinds of communication systems such as radio or microwave. For example, nearly all long-distance telephone calls are carried by optical communication systems because a single optical fiber can carry thousands of conversations at the same time. Optical systems also offer the potential of carrying large quantities of digital data for high-speed computers more efficiently and economically than other communication systems.

Every optical communication system includes, at a minimum, three elements: a transmitter that generates a beam of light and modulates the beam with data to be transmitted, a receiver that receives the beam of light and recovers the data from it, and a medium such as an optical fiber that carries the beam of light from the transmitter to the receiver. Typically the transmitter uses a laser or a light-emitting diode ("LED") to generate the light beam. The receiver uses photodetectors or the like to receive the beam. The medium may be an optical waveguide or the like instead of an optical fiber.

Light may travel through an optical medium in single mode or multiple modes. In general, a "mode" of an electromagnetic wave can be defined as a stationary pattern of the wave. In the special case of a beam of light (which may be thought of as an electromagnetic wave in the optical portion of the spectrum), a mode is a wave pattern that does not change the shape of its transverse field distribution as it propagates through the medium.

A given optical medium may be capable of supporting many modes or only a single mode. This is determined by physical parameters such as—in the case of an optical fiber—the diameter of the fiber and the difference between the indices of refraction of the core and the cladding.

Likewise, many lasers can be caused to operate in single mode or in multiple modes. This can be done by a suitable choice of device structure and drive conditions. Multiple mode operation has generally been understood to consist of multiple modes in one laser cavity. However, studies have shown that multiple mode laser operation can occur with filamentation due to non-uniform gain or loss. This is especially true for lasers with large transverse dimensions compared with the wavelength. For convenience, the terms "multiple mode" and "multimode" as used herein to describe the operation of a laser will include both multiple modes in a single laser cavity and multiple filamentation.

Optical communication systems are subject to various kinds of losses and limitations. Among these are intermodal dispersion, chromatic dispersion and mode selective losses. All of these have the effect of decreasing the signal-to-noise ratio, and therefore it is desirable to eliminate or minimize them as much as possible.



Intermodal dispersion becomes worse as the length of the fiber increases. Intermodal dispersion only affects multimode fibers, and therefore single mode fibers are preferred for communication over long distances. As used herein, a "long" distance means a distance that is more than a few hundred meters and a "short" distance is one that is less than a few hundred meters. Of course, it should be understood that this is an approximation; multimode fibers up to a few kilometers in length have been used successfully, but usually when the required length of the fiber exceeds a couple of hundred meters a single mode fiber will be used.

Chromatic dispersion also becomes more severe as the length of the fiber increases but, unlike intermodal dispersion, chromatic dispersion affects both single mode and multimode fibers. The adverse effects of chromatic dispersion can be minimized by using a highly coherent laser because such a laser produces a light beam of very narrow spectral width. Accordingly, highly coherent lasers have been preferred for most optical communication systems, especially for communication over long distances.

Of course, single mode optical fibers can also be used over short distances (less than a few hundred meters), for example to carry digital data from one computer to another in a local network or even to carry data between points less than a meter apart within a single computer. However, multimode optical fibers are preferred for short-distance optical communication systems because their relative ease of packaging and alignment makes them considerably less expensive than single mode fibers.

A drawback of multimode optical media has been that these media are subject to mode selective losses. A mode selective loss may be characterized as a physical condition that affects the optical characteristics of the medium. These losses may be, for example, splices in the medium, power splitters and other devices that are connected to the medium, and physical defects such as poor quality connections and misalignment of components. Although such physical conditions can be reduced by careful design and construction, in practice it is rarely possible to produce a system that is totally free of them. Therefore, all practically realizable multimode optical communication systems will be subject to at least some mode selective losses.

The actual mechanism by which physical discontinuities produce mode selective losses will now be briefly discussed. Interference between different modes in a multimode medium carrying a coherent light beam produces a speckle pattern. Ideally this speckle pattern would remain stationary, but in practice it moves about within the medium. Speckle pattern movement may be caused by physical jostling or other movement of the fiber itself (relatively slow movement) or by laser mode partitioning and the like (relatively fast movement). Movement of the speckle pattern in a system having mode selective losses results in power variations in the received signal. These variations are caused by the mode selective losses and result in a degradation of the signal-to-noise ratio. In digital systems, a degradation of the signal-to-noise ratio manifests itself as an increased bit error rate.

Mode selective losses are described in more detail in such references as Epsworth, R. E., "The Phenomenon of Modal Noise in Analogue and Digital Optical Fibre Systems", *Proceedings of the 4th European Conference on Optical Communications*, Genoa, September, 1978, pp. 492–501, and in Kanada, T., "Evaluation of Modal Noise in Multimode Fiber-Optic Systems", *IEEE Journal of Lightwave Technology*, 1984, LT-2, pp. 11–18.

Mode selective losses can be avoided by using a relatively low-coherence light source such as an LED or a self-pulsating laser diode ("SPLD") rather than a highly coherent laser. The use of LEDs in optical communication systems is described in Soderstrom, R., et al., "Low Cost High Performance Components of Computer Optical Data Links", *Proceedings of the IEEE Laser and Electrooptics Society Meeting*, Orlando, Fla. 1989. A disadvantage of using LEDs in optical communication systems is that the coupling efficiency between an LED and an optical fiber is very low. In addition, LEDs are inherently slow, which limits the maximum data rate.

SPLDs have been used in such systems as the Hewlett-Packard HOLC-0266 Mbaud Fiber Channel multimode fiber data link, manufactured by the assignee hereof; this is described in Bates, R. J. S., "Multimode Waveguide Computer Data Links with Self-Pulsating Laser Diodes", *Proceedings of the International Topical Meeting on Optical Computing*, Kobe, Japan, April, 1990, pp. 89–90. The coupling efficiency between an SPLD and an optical fiber is better than that between an LED and an optical fiber, but still is not optimal. In addition, the maximum data rate that can be achieved with an SPLD is limited. Neither SPLD nor LED systems have been able to achieve reliable data rates as high as 1 gigabit per second

From the foregoing it will be apparent that there remains a need for a reliable and economical way to carry data at rates exceeding one gigabit per second by means of optical communication systems operating over short distances.

## SUMMARY OF THE INVENTION

The present invention provides an optical communication system that can transmit data reliably and economically by means of multimode optical media at any rate up to and exceeding one gigabit per second.

Briefly and in general terms, the invention is embodied in an optical communication system having a vertical-cavity, surface-emitting laser ("SEL"). A multimode optical medium such as an optical fiber is coupled to the SEL. A power supply provides a bias current that drives the SEL into multiple transverse mode operation, preferably in more than two distinct modes. The SEL generates a beam of light that has a lower coherence than that provided by a single-mode laser. This beam of light is modulated with data carried by an incoming signal. The SEL preferably has an aperture larger than about eight micrometers ("μm") through which the modulated light beam is emitted.

The optical medium carries the modulated beam of light from the SEL to a receiver at a remote location. The receiver, which may be closer than a meter or farther away than 100 meters, recovers the data from the light beam.

Other aspects and advantages of the invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, illustrating by way of example the principles of the invention.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic diagram of a preferred embodiment of an optical communication system according to the invention; and

FIG. 2 is a cross-sectional view of a vertical-cavity, surface-emitting laser of the kind used in the communication system shown in FIG. 1.

## DESCRIPTION OF THE PREFERRED EMBODIMENT

As shown in the drawings for purposes of illustration, the invention is embodied in a novel optical communication system having a vertical-cavity, surface-emitting laser ("SEL") driven into multiple transverse mode operation to provide a light beam that carries data reliably and efficiently over a multimode optical medium. To avoid the expense of single mode fibers for communicating over distances of less than a few hundred meters, existing optical communication systems have used multimode fibers, but such systems have been subject to unacceptably high mode selection losses or have used low-coherence light sources such as LEDs and SPLDs that have not been able to achieve sufficiently high data rates.

A communication system according to the invention uses an SEL operating in multiple transverse modes. The SEL provides a beam of light that has lower coherence than the highly-coherent light beams typically used in single mode systems but higher coherence than the low-coherence beams provided by LEDs and self-pulsating lasers. A multimode optical medium carries the beam from the SEL to a receiver which may be less than a meter away or 100 meters or more distant. The system can transmit data at any rate up to and exceeding 1.5 gigabits per second with a negligible bit error rate. The system provides all the benefits, such as easy alignment, simple packaging and low cost, usually associated with multimode optical media.

A preferred embodiment of the invention will now be discussed in more detail. As shown in FIG. 1, the invention is embodied in an optical communication network that includes an SEL **11**, a power supply **13** that provides a bias current to drive the SEL into multiple transverse mode operation, and a multimode optical medium **15** optically coupled to the SEL to carry the optical signal from the SEL to a remotely-located receiver **17**. The SEL is responsive to a signal carrying data (designated generally as **19**) to provide an optical signal modulated with the data. The receiver **17**, which is optically coupled to the optical medium **15**, receives the modulated optical signal and recovers the data (designated generally as **21**) therefrom.

Various kinds of multimode optical media such as optical fibers and waveguides may be used for the medium **15**. The SEL **11** and the receiver **17** are coupled to the medium **15** through suitable couplings **23** and **25**. As will be discussed in more detail presently, the SEL **11** is preferably driven in more than two distinct transverse modes; as noted previously, this may comprise multiple filamentation.

A preferred method of fabricating the SEL **11** is illustrated in FIG. 2. The SEL is grown on an n+GaAs (gallium arsenide) substrate **31**. A bottom output mirror, for example 18.5 pairs of n-doped GaAs/AlAs (gallium arsenide/aluminum arsenide) quarter-wave layers (generally designated **33** in the drawing), is epitaxially grown on the substrate **31**. The interface between the

layers is graded using an AlAs/GaAs/Al(0.3)Ga(0.7)As variable duty cycle short period superlattice ("SPSL"). The SPSL reduces any heterojunction band discontinuities at the GaAs/AlAs interface. The doping level is $1\times10^{18}cm^{-3}$ in uniform regions and $3\times10^{18}cm^{-3}$ in graded regions. For simplicity only a few of the 18.5 pairs of layers are shown in the figure. The reflectivity of the bottom mirror **33** is 98.9%.

Next an optical cavity structure **35** is grown. The cavity structure includes an n-cladding layer **37**, a quantum well **39**, and a p-cladding layer **41**. The cladding layers **37** and **41** comprise Al(0.3)Ga(0.7)As doped to $1\times10^{18}cm^{-3}$, reduced to $5\times10^{17}cm^{-3}$ adjacent the quantum well **39**. The quantum well **39** comprises 3 MQW of strained In(0.2)Ga(0.8)As (indium gallium arsenide) having a thickness of about 80 Å (Å=Angstrom), with GaAs barriers having a thickness of 100 Å.

Above the quantum well **35** is a highly-reflective top mirror **43**. The reflectivity of the top mirror is greater than 99.96%. The top mirror **43** comprises, for example, 15 pairs of GaAs/AlAs quarter wave layers (generally designated **45**), a phase matching layer **47**, and an Au (gold) layer **49**. A proton isolation region **51** surrounds the perimeter of the quarter wave layers **45**. As with the bottom mirror **33**, only a few of the quarter wave layers **45** are actually shown in FIG. **2**. The interfaces between the quarter wave layers are graded in a manner generally similar to the grading of the interfaces in the bottom mirror **33**. The doping levels are $1\times10^{18}cm^{-3}$ in uniform regions and $5\times10^{18}cm^{-3}$ in graded regions.

The phase matching layer **47**, which is GaAs, compensates for phase delays that result from finite penetration of the optical field into the Au layer.

The Au layer **49** is about 2000 Å thick and is fabricated, after MBE growth of the underlying structure, as follows. First a 2000 Å layer of Au is deposited on the GaAs phase matching layer **47**. Then a thick (more than 10 μm) Au button is plated on top to serve as a mask for proton isolation. The wafer is then proton implanted. Crystal structure damage that results from the proton implantation provides for current confinement and therefore gain guiding. Then another thick Au button **53** with a diameter of about 300 μm is plated on top. This button **53** is used for solder/die attachment of the completed device to a heat sink. The wafer is then lapped and polished to a diameter of 125 μm and an annular electrode **55** is patterned on the bottom. A quarter-wave anti-reflection coating **57** of $SiO_2$ (silicon dioxide) is deposited in the open region of the electrode **55**.

An optical communication system embodying the principles of the invention was constructed using a relatively large-area SEL with a 25 μm opening coupled to an optical fiber. A physical discontinuity was deliberately introduced into the fiber; this discontinuity was a gap of several millimeters. The gap was adjustable to cause between 3 dB and 16 dB of loss. The length of the fiber between the SEL and the gap was 16 meters; this portion of the fiber was agitated with a shaker to simulate the effect of fiber movement. The bit error rate ("BER") was measured for gaps of various widths; the measured BERs were less than $10^{31\ 11}$ for losses up to 10 dB.

In the tests described herein, a wavelength of about 970 nanometers ("nm") was used. It will be apparent that the principles of the invention are equally applicable to devices that are operated at other wavelengths, and that the physical dimensions will change accordingly.

In another test the performance of the large-area SEL was compared with that of a smaller SEL having a 12 μm opening. The threshold currents were about 6.5 milliamps (mA) for the large SEL and 4.2 mA for the smaller. The threshold voltages were 2.7 and 4.5 volts, respectively. The output power at twice the threshold current was 3.6 milliwatts (mW) for the larger SEL and 2.8 mW for the smaller. The emission wavelength was about 970 nm.

The SELs were modulated directly by a 1 gigabit-per-second, non-return-to-zero ("NRZ") signal at a maximum of 2 volt amplitude and with a $2^{15}-1$ pseudo-random bit sequence through a bias-T. The bias levels were several times the respective threshold currents. The SELs were directly coupled into 50/125 graded index multimode fiber. The length of the fiber between the SEL and the gap was 16 meters, and the gap was adjusted for a 10 dB loss. An optical attenuator was inserted between the gap and the receiver to keep the optical power incident on the receiver at 6 dB above the receiver sensitivity.

The receiver was a Hewlett-Packard model 83442A receiver modified for multimode use with a 60 μm InGaAs detector and a multimode FC/PC input connector. The receiver had a −3 dB bandwidth of 0.9 GHz. The AC-coupled receiver output was amplified to 2.0 volts before detection. The sensitivity of the receiver was −23 dBm for a receiver noise-limited BER of $10^{-9}$.

In this test configuration, the 25 μm SEL was operated for 16 hours without an error, resulting in a BER of less than $10^{-13}$. In other tests, the length of the fiber between the SEL and the gap (the gap was adjusted to a 10 dB loss) was varied between six and 406 meters and in every such instance the BER was less that $10^{-11}$. The 12 μm SEL was also able to achieve a BER of less than $10^{-11}$ with the gap adjusted to about a 4 dB loss.

A strongly-driven SEL with a relatively large surface area ("large surface area" means a surface opening larger than about eight μm) will operate in multiple, high-order transverse modes that are at slightly different wavelengths. As the size of the opening increases, so does the maximum number of transverse modes that can be obtained. Thus, an SEL with a 25 μm opening can be operated in significantly more transverse modes than an SEL with a 12 μm opening.

As the number of transverse modes increases, the optical bandwidth of the light produced by the laser also increases and the coherence of the light decreases. Speckle visibility measurements have shown that the speckle visibility from a large-area SEL is smaller than that of smaller SELs.

Despite operating in multiple transverse modes, the large-area SEL operates in a stable, single longitudinal mode. Longitudinal mode partition noise, which results from multiple longitudinal modes, is therefore not a significant problem with large-area SELs.

In one test, a 25 μm SEL was found to be operating in at least six distinct transverse modes at a drive current of 2.3 times the threshold current. The spectral width was $\Delta\lambda=0.75$ nm. When the drive current was reduced sufficiently to cause the laser to go into single mode operation, the spectral width was $\Delta\lambda<0.08$ nm; this measurement was limited by the resolution of the optical spectrum analyzer that was used for the test. In contrast, a 12 μm SEL was found to be operating in

single mode at a drive current 1.5 times the threshold and in two transverse modes at a drive current 2.5 times the threshold.

From the foregoing it will be apparent that an optical communication system according to the invention is capable of carrying digital data at rates up to and exceeding 1.5 gigabits per second with very low bit error rates. The invention also offers the advantages, such as easy alignment, simple packaging and low cost, that are associated with systems using multimode optical media. In addition, SELs are expected to be easier and less expensive to manufacture than other kinds of lasers.

Although a specific embodiment of the invention has been described and illustrated, the invention is not to be limited to the specific forms or arrangements of parts so described and illustrated, and various modifications and changes can be made without departing from the scope and spirit of the invention. Within the scope of the appended claims, therefore, the invention may be practiced otherwise than as specifically described and illustrated.

We claim:

1. An optical communication network comprising:

a vertical-cavity, surface-emitting semiconductor laser structure having an aperture larger than eight micrometers through which an optical signal may be emitted;

a power supply that provides a bias current to drive the laser into a multiple transverse mode of Operation in which the laser is responsive to a signal carrying data to provide an optical signal modulated with the data and to emit the optical signal through the aperture; and

a multimode Optical medium optically coupled to the laser to carry the optical signal from the laser to a remotely-located receiver.



2. A network as in claim 1 and further comprising a receiver, optically coupled to the optical medium, that receives the modulated optical signal and recovers the data therefrom.

3. A network as in claim 1 wherein the multiple transverse mode of operation comprises more than two distinct transverse modes.

4. A network as in claim 1 wherein the multiple transverse mode of operation comprises multiple filamentation.

5. A network as in claim 1 wherein the multi-mode optical medium comprises an optical fiber.

6. A network as in claim 1 wherein the multi-mode optical medium comprises an optical waveguide.

* * * * *

| L Number | Hits | Search Text | DB | Time stamp |
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| 4 | 2 | ("5359447").PN. | USPAT; US-PGPUB; EPO; JPO; DERWENT | 2004/01/14 11:55 |

US005386490A

# United States Patent [19]

Pan et al.

[11] **Patent Number: 5,386,490**

[45] **Date of Patent: Jan. 31, 1995**

[54] **AUTOMATED WORKSTATION FOR THE MANUFACTURE OF OPTICAL FIBER COUPLERS**

[75] Inventors: **Jing-Jong Pan**, Milpitas; **Frank Y. F. Liang**, San Jose; **Ming M. Shih**, Milpitas; **Zhong M. Mao**, Santa Clara; **Kung Shih**, San Jose, all of Calif.

[73] Assignee: **E-Tek Dynamics, Inc.**, San Jose, Calif.

[21] Appl. No.: **86,629**

[22] Filed: **Jul. 1, 1993**

[51] **Int. Cl.**$^6$ ............................ **G02B 6/00**; G02B 6/36

[52] **U.S. Cl.** ........................................ **385/134**; 385/95

[58] **Field of Search** ..................... 385/134, 137, 95, 97

[56] **References Cited**

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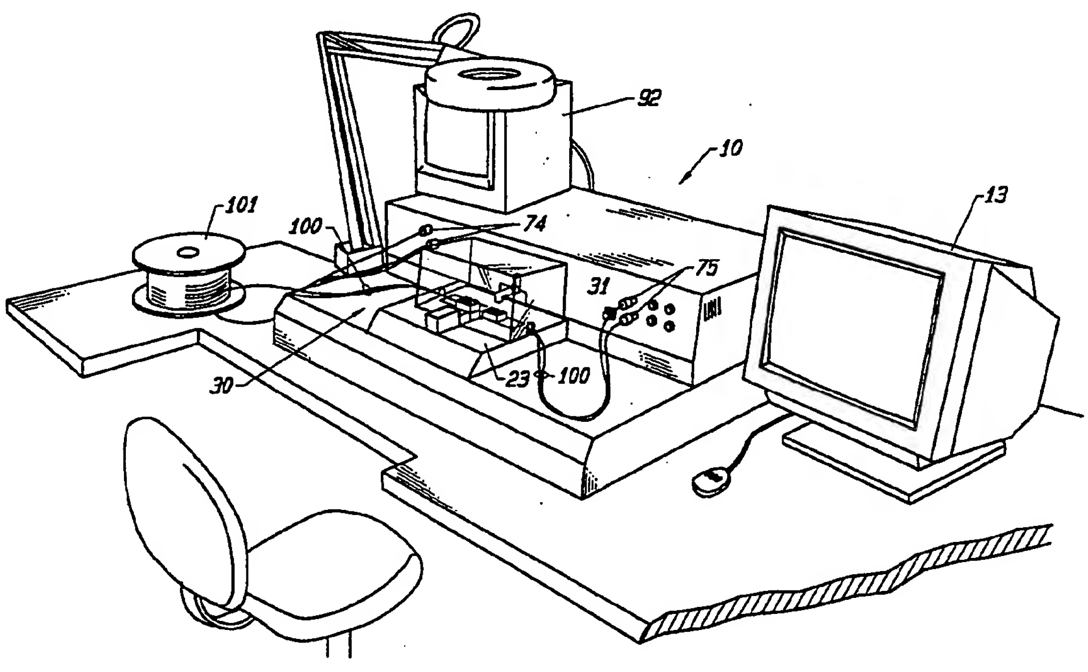
*Primary Examiner*—Akm E. Ullah

*Attorney, Agent, or Firm*—Townsend and Townsend Khourie and Crew

[57] **ABSTRACT**

The present invention provides for a workstation for automatically manufacturing a coupler between at least two optical fibers. The workstation has a control unit for directing operations of said workstation and an operations unit for performing the manufacturing steps for the coupler. The operations unit has a pair of clamps for holding the optical fibers for the formation of a coupling region between the clamps, a torch for heating a predetermined length of the fibers between the clamps to fuse the fibers, motor assemblies responsive to the control unit for driving the clamps, a source laser block for generating an input signal into the optical fibers, and a laser measurement block which measures the signal from laser source block to determine characteristics of the coupling region between the optical fibers.

**20 Claims, 16 Drawing Sheets**



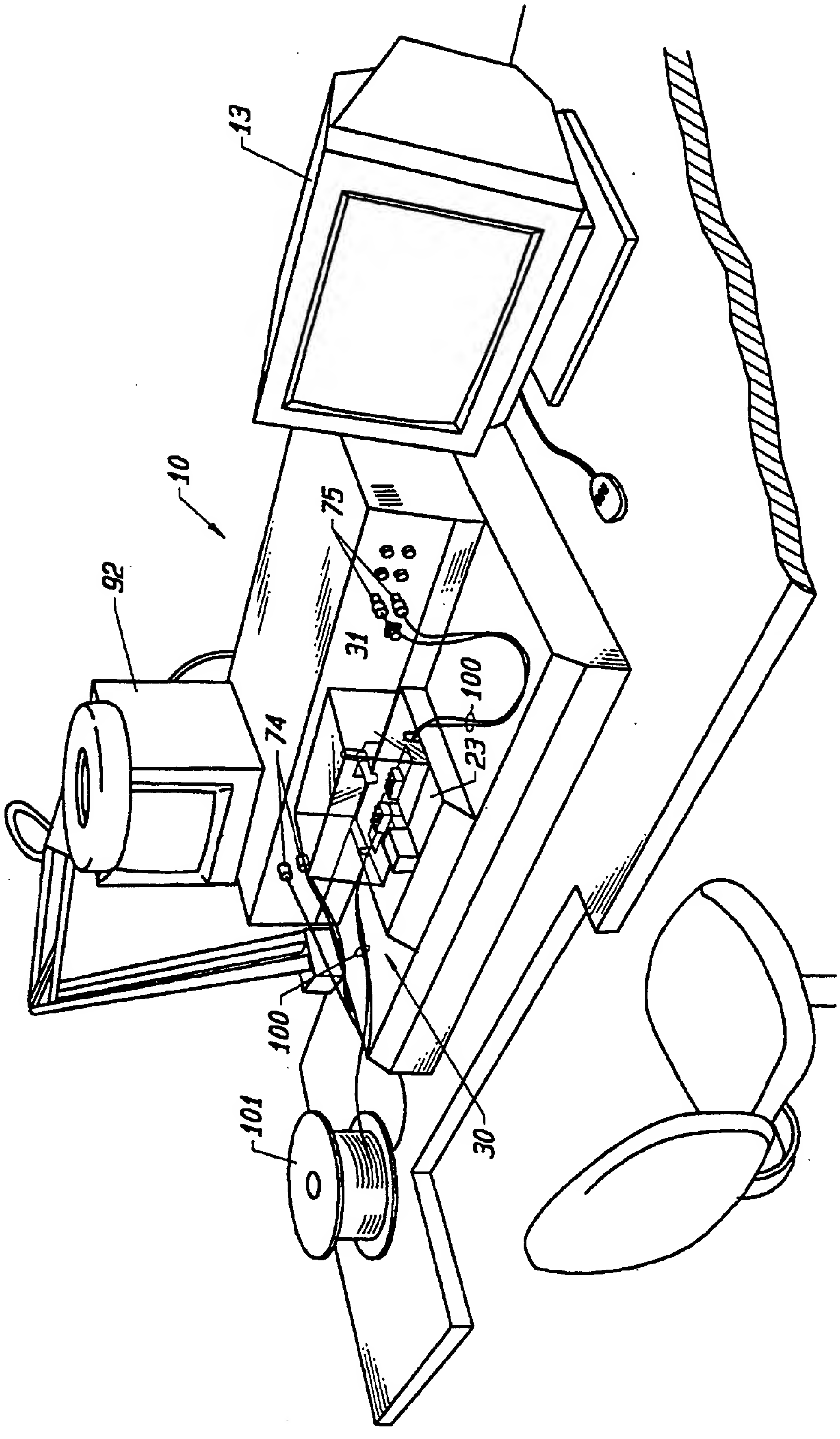
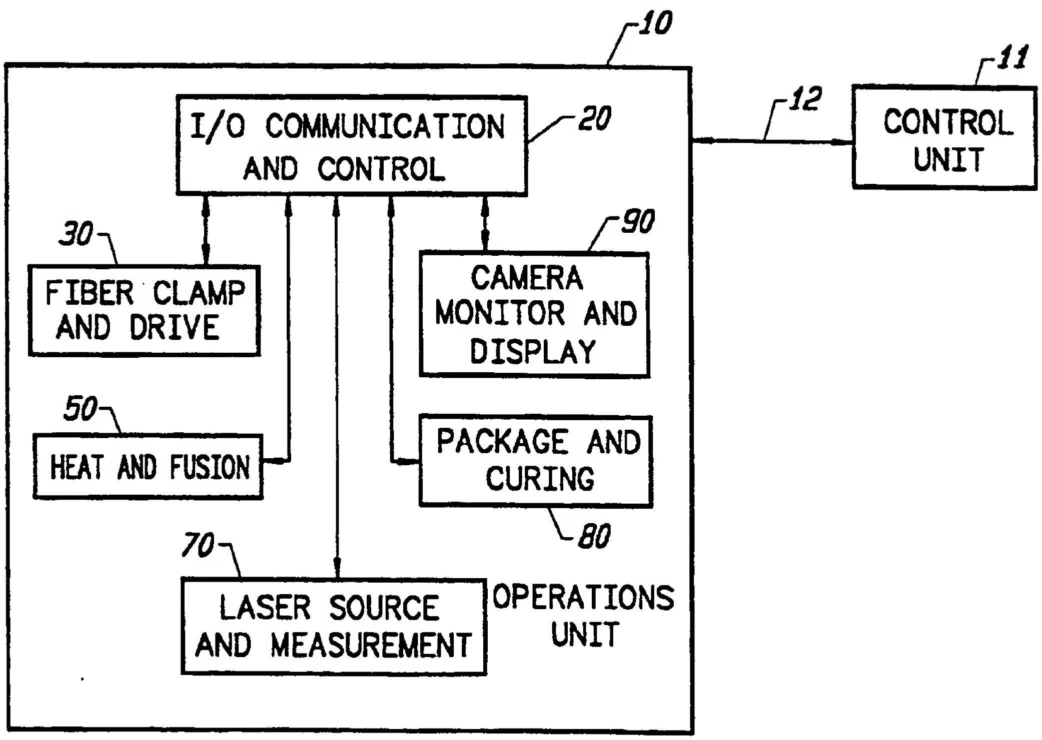



FIG. 1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FIBER CLAMP AND DRIVE
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CAMERA MONITOR AND DISPLAY
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HEAT AND FUSION
PACKAGE AND CURING
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70
LASER SOURCE AND MEASUREMENT
OPERATIONS UNIT

FIG. 2

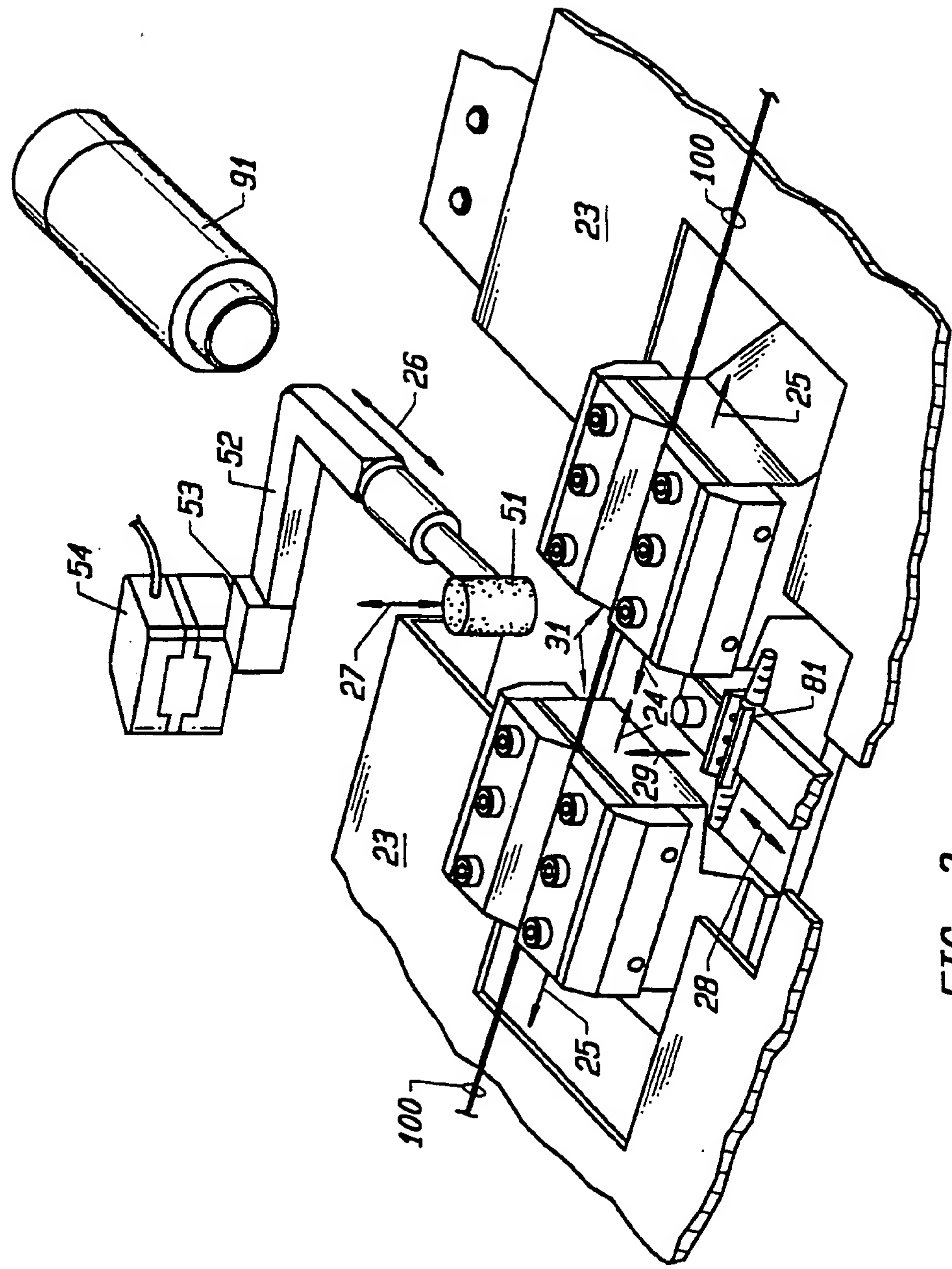



FIG. 3

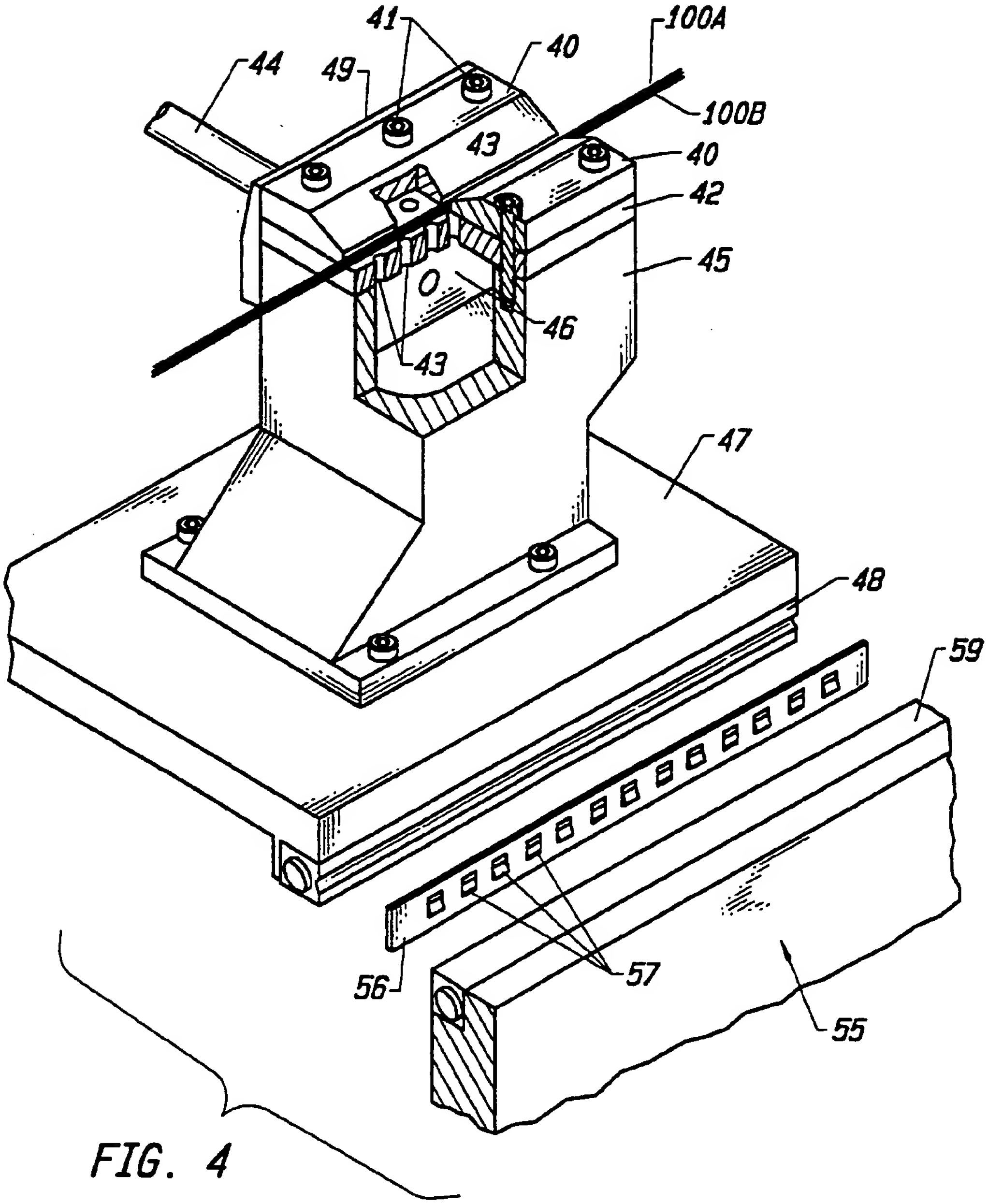



FIG. 4

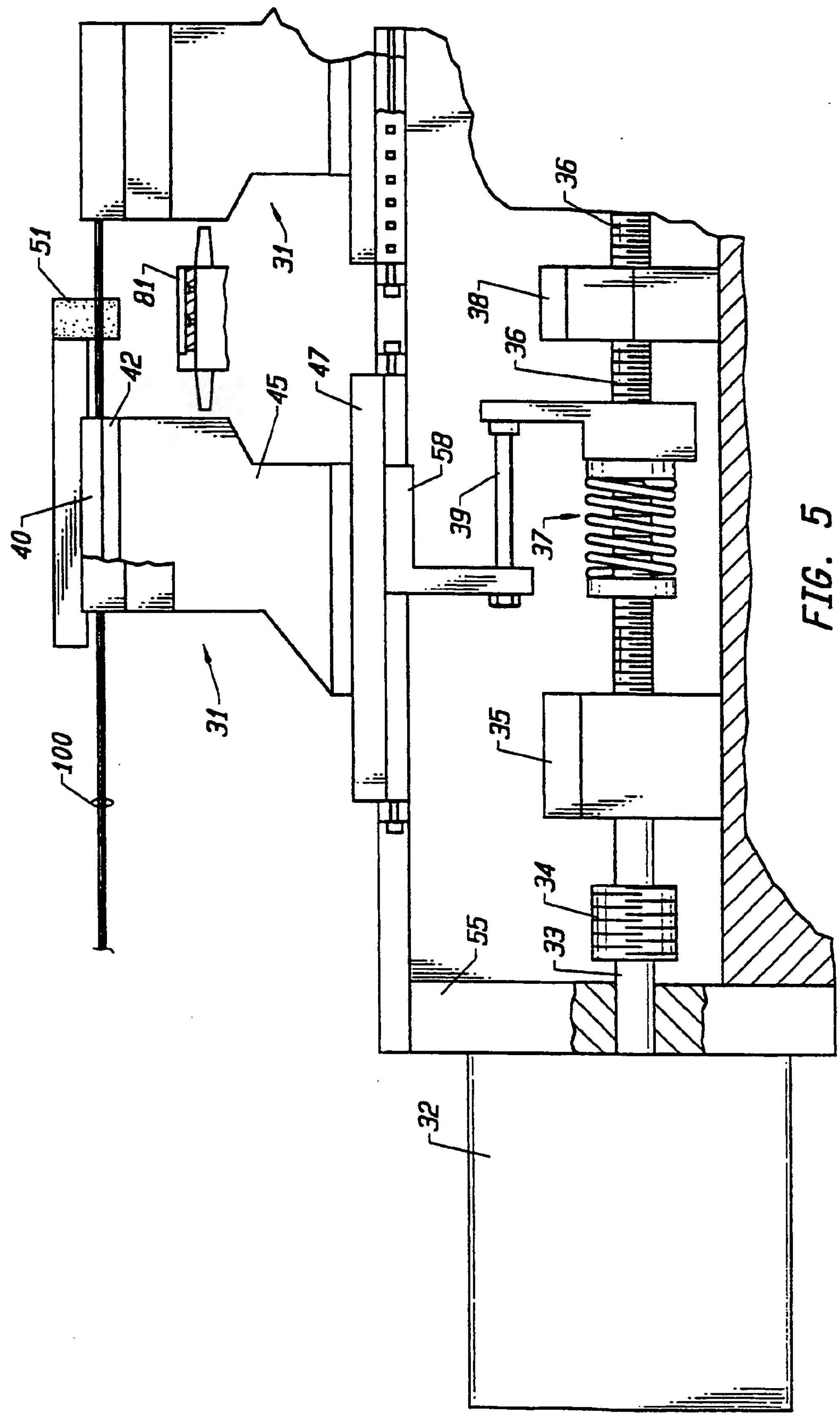
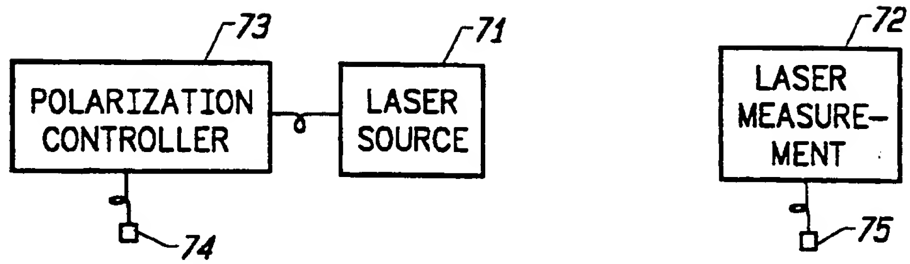



FIG. 5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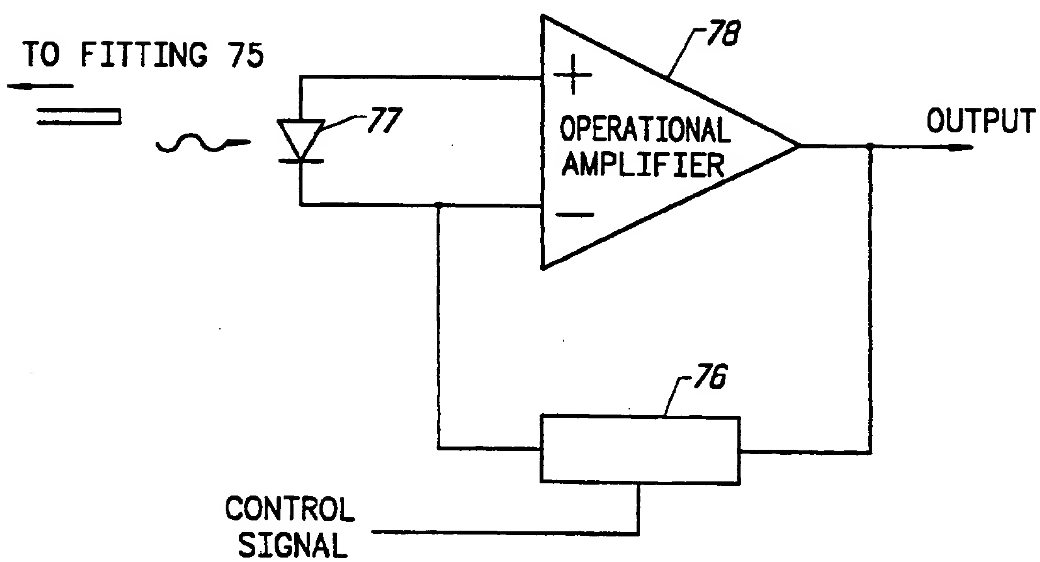
CONTROLLER
LASER
SOURCE
LASER
MEASURE-
MENT
74
75

FIG. 6A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OUTPUT
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CONTROL
SIGNAL

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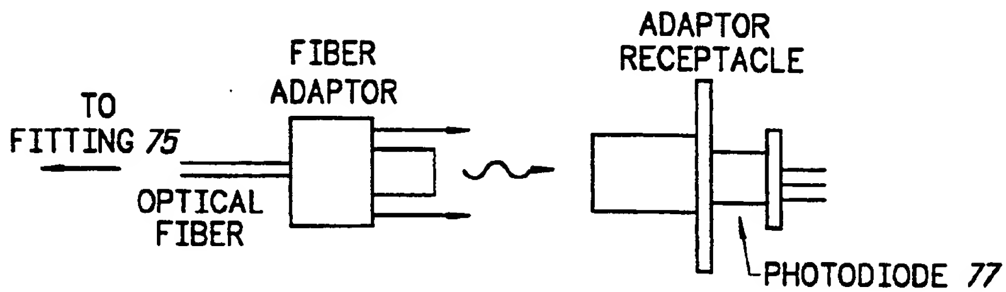
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FIG. 6C

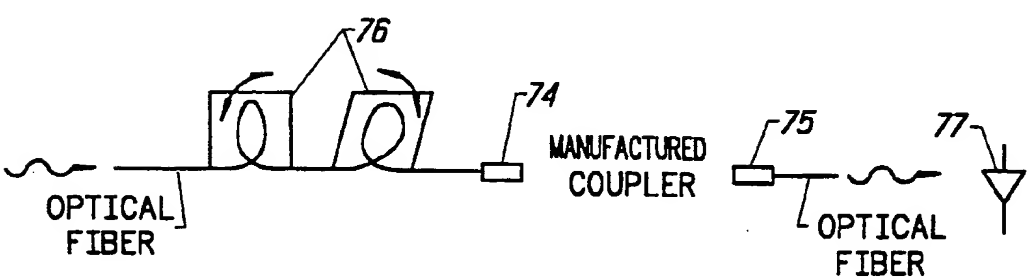
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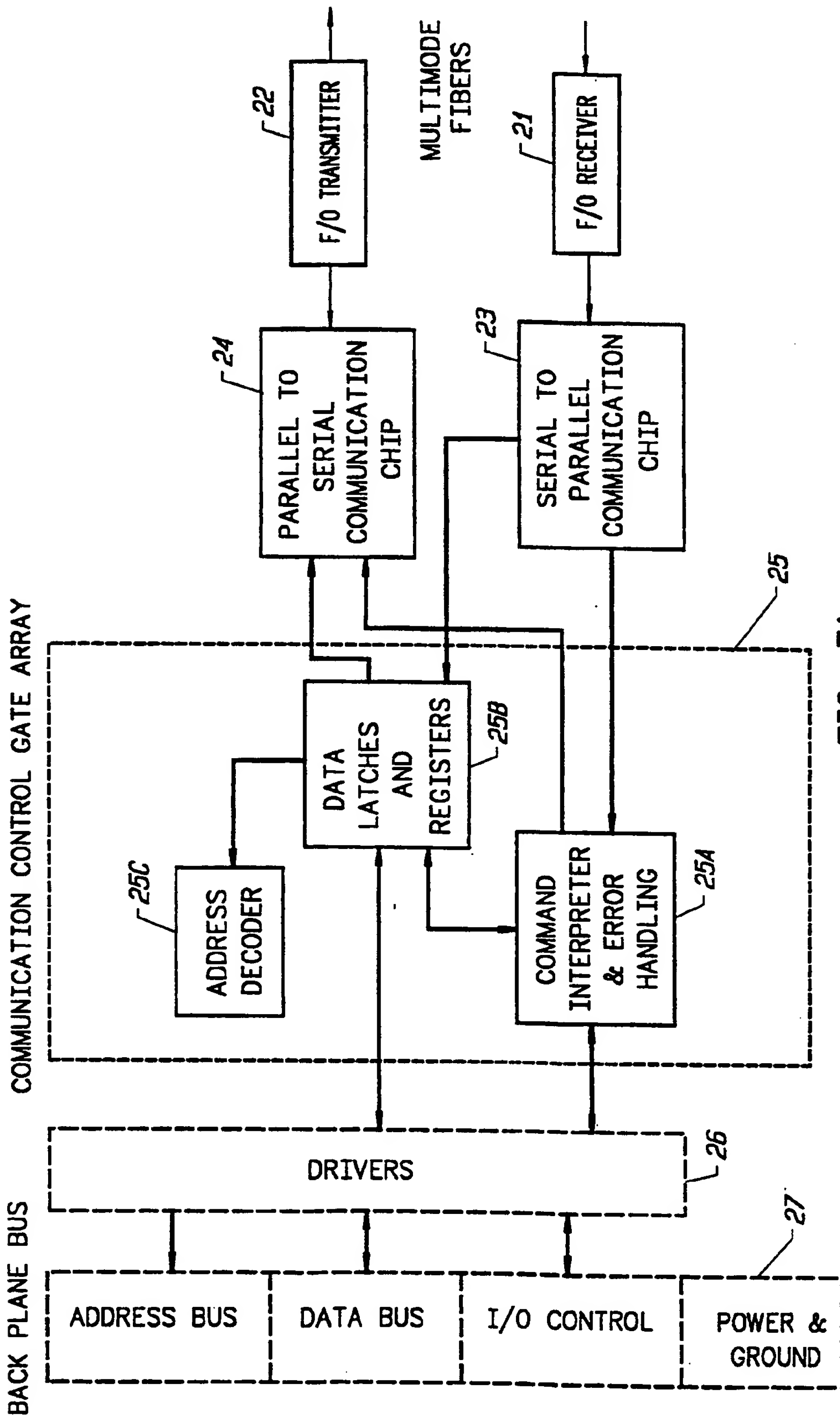
FIG. 6D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F/O RECEIVER
24
PARALLEL TO SERIAL COMMUNICATION CHIP
23
SERIAL TO PARALLEL COMMUNICATION CHIP
COMMUNICATION CONTROL GATE ARRAY
25
DATA LATCHES AND REGISTERS
25B
25C
ADDRESS DECODER
COMMAND INTERPRETER & ERROR HANDLING
25A
DRIVERS
26
27
BACK PLANE BUS
ADDRESS BUS
DATA BUS
I/O CONTROL
POWER & GROUND

FIG. 7A

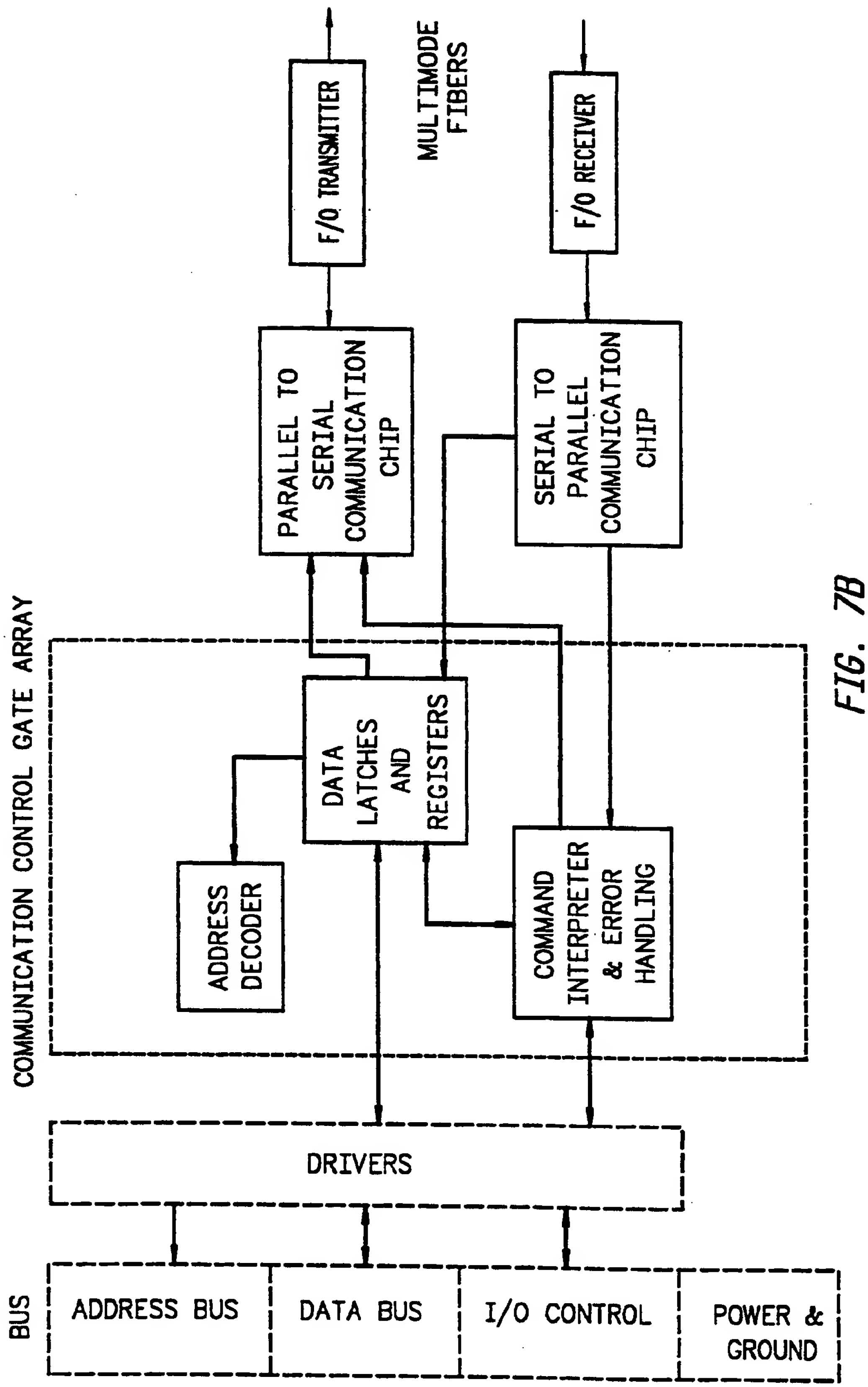

MULTIMODE FIBERS
F/O TRANSMITTER
F/O RECEIVER
PARALLEL TO SERIAL COMMUNICATION CHIP
SERIAL TO PARALLEL COMMUNICATION CHIP
COMMUNICATION CONTROL GATE ARRAY
DATA LATCHES AND REGISTERS
ADDRESS DECODER
COMMAND INTERPRETER & ERROR HANDLING
DRIVERS
BUS
ADDRESS BUS
DATA BUS
I/O CONTROL
POWER & GROUND

FIG. 7B

**FABRICATION PROGRAM**

1. Initialize and display ready message.
2. Get time, date, pulling motor position, read PDs, calculate CRs and EL.
3. Display time, date, pulling motor position, PDs, CRs and EL.
4. System Check: Link check -Display link normal or failure message.
   Gas leak check -Shut off gas flow and alarm operator on gas leak.
5. Activate appropriate routine if button is pressed.

| | | |
|---|---|---|
| Operation buttons: | a. RECAL | Recalibrate |
| | b. HOME | Home |
| | c. PPULL | Pre-Pull |
| | d. PULL | Pulling |
| | e. PULL++ | Pull++ |
| | f. PACK/DEPACK | Packaging and Depacking |
| | g. PST | Polarization |
| | h. Next... | Next operation |
| | i. ZERO | Record PD offsets |
| | j. STOP | Stop current operation |
| | k. EXIT | Quit fabrication program |
| Vacuum buttons: | l. Pull Left | Left pulling vacuum |
| | m. Pull Right | Right pulling vacuum |
| | n. Package | Packaging vacuum |
| Heater button: | o. OFF | Heater control |
| | p. AUTO | Auto heater control |
| Gas Flow button: | q. OFF | Turn gas flow ON/OFF manually |

6. Goto 2.

<u>Operation Buttons</u>

**RECAL (Recalibrate)**

1. Initialize and display operation message.
2. If fabrication data has not been saved, save to data base.
3. Move motors a few steps away from home position.
4. If motor stops but still remains at home position, display error message and wait for operator clicking on "OK" button and then goto 8.
5. Move motors MAX_STEP toward home position.
6. If motor stops but not at home position, display error message and wait for operator clicking on "OK" button and goto 8.
7. Move motors to ready position.
8. Display next operation message.
9. Return to fabrication program.

**FIG. 8A**

**HOME (Homing)**

1. Initialize and display operation message.
2. If fabrication data has not been saved, save it to data base.
3. Move packaging holder and torch backward to home position.
4. Move fiber holder to starting-offset position.
5. Move fiber holder to starting position.
6. Display next operation message.
7. Return to fabrication program.

**PPULL (PrePull)**

1. Move torch forward to fusion position.
2. Delay preset Pull Delay time.
3. Move fiber holder outward a preset step.
4. Return to fabrication program.

**PULL (Pulling)**

1. Initialize and display operation message.
2. Move torch forward to fusion position.
3. Delay preset Pull Delay time.
4. Move fiber holder outward.
5. Stop fiber holder when PD readings reach preset settings or fiver holder position reach its limit of the "STOP" button has been pressed.
6. Move torch to home position.
7. Delay preset Stop Delay time.
8. Keep the CRs, EL, pulling length data in memory for record.
9. Display next operation message.
10. Return to fabrication program.

**PULL++ (Pull++)**

1. Move fiber holder outward 20 steps.
2. Return to fabrication program.

**PACK (Packaging)**

1. If fiber holder gap is too narrow, display warning message and goto 6.
2. Initialize and display operation message.
3. Move packaging holder forward to the position below the fused fiber.
4. Move packaging holder upward to the packaging position.
5. Display next operation message.
6. Return to fabrication program.

**FIG. 8B**

**DEPACK**

1. Initialize display operation message.
2. Turn off package vacuum valve.
3. Move packaging holder downward to starting position.
4. Move packaging holder backward to home position.
5. Display next operation message.
6. Return to fabrication program.

**PST (Polarization)**

1. Initialize and display operation message.
2. Return polarization controller to home position.
3. Move quarter lambda controller to starting position.
4. Move half lambda controller one step at a time from starting position (home) to stopping position and collect PD readings on each step.
5. Calculate PST from collected PD readings. [PST (%) = CR (max.) - CR (min.)]
6. Keep PST value in memory for record.
7. Display next operation message.
8. Return to fabrication program.

**NEXT... (Next Operation)**

Next button will activate the next operation.

| | Current Operation | Next Operation |
|---|---|---|
| a. | Pulling Vacuums ON | b. |
| b. | PULL | c. |
| c. | Package Vacuum ON | d. |
| d. | PACK | e. |
| e. | Auto Heat | f. |
| f. | DEPACK | g. |
| g. | PST | h. |
| h. | Pulling Vacuums OFF | i. |
| i. | HOME | a. |

**ZERO (Record PD Offsets)**

1. Record PD Offsets.

| | |
|---|---|
| "Yes" | -record PD offsets |
| "No" | -clear PD offsets |
| "Cancel | -no change |

2. Return to fabrication program.

FIG. 8C

**STOP (Stop current operation)**

1. Depending on the current operation routine, different action will be performed.

| Current Operation | Action |
|---|---|
| RECAL | -Stop all operating motors<br>-Stop all operation timers<br>-Goto step 8 in RECAL routine |
| HOME | -Stop fiber holder<br>-Goto step 6 in HOME routine |
| PULL | -Goto step 6 in PULL routine |
| PACK | -Stop packaging holder<br>-Goto step 5 in PACK routine |
| Auto Curing | -Turn off heat and stop curing timer |
| DEPACK | -Stop packaging holder<br>-Goto step 5 in DEPACK routine |
| PST | -Stop polarization controller<br>-Goto step 7 in PST routine |

2. Return to fabrication program.

**EXIT (Quit fabrication program)**

1. If data has not been saved, save it to data base.
2. Stop all timers.
3. Save all motor positions to data file.
4. Return to main program.

<u>Vacuum Buttons</u>

**Pull Left**

1. Toggle ON/OFF left pulling vacuum valve.
2. Return to fabrication program.

**Package**

1. Toggle ON/OFF packaging vacuum valve.
2. Return to fabrication program.

<u>Heater Buttons</u>

**ON/OFF**

1. Toggle ON/OFF heater
2. Return to fabrication program.

FIG. 8D

**Auto (Auto curing)**

1. Initialize and display operation message.
2. Start curing timer and turn on heat.
3. Turn OFF heat after curing time expired or "STOP" button has been pressed.
4. Display next operation message.
5. Return to fabrication program.

FIG. 8E

FABRICATION DATA FILE

| ... Data Field | Data Format | Unit | Description |
|---|---|---|---|
| 1. Station ID | Integer | | Station ID Number |
| 2. Operator ID | Integer | | Operator ID Number |
| 3. Lot Number | String (10) | | Lot number of coupler |
| 4. Coupler Number | Integer | | Number that assign to this coupler |
| 5. Wavelength | Integer | nm | Wavelength of laser diode |
| 6. CR Spec | String (9) | | Required CR Specification |
| 7. Date | Date | | Date of fabrication |
| 8. Time | String (8) | | Time of fabrication |
| 9. Pref | Float | μW | PD reference during fabrication |
| 10. EL | Float | dB | Excess loss of coupler |
| 11. CR | Float | % | Coupling ratio of coupler |
| 12. PST | Float | % | Polarization of coupler |
| 13. Pull Length | Float | mm | Pulling length of coupler |

QUALIFIED RECORDS DATA FILE

| Data Field | Data Format | Description |
|---|---|---|
| 1. Record Number | Integer | Record number in fabrication data file. |

STATISTICAL ANALYSIS

1. Define record selection criterias.
2. Start from the first records of fabrication data file.
3. Compare each fabrication record with the record selection criterias, store the record number of qualified record into qualified record data file and collect qualified record data to calculate the statistics.
4. Repeat step 3 until the last record of fabrication data file.
5. Display statistical results on screen.

DISPLAY QUALIFIED RECORDS

1. Records that match the record selection criterias are stored in qualified records data file.
2. Available record display option:

| | |
|---|---|
| TOP | -Display the first qualified record data |
| BOTTOM | -Display the last qualified record data |
| NEXT | -Display next qualified record data |
| PREV | -Display previous qualified record data |
| Record Number | -Display qualified record data of a specific record number |

FIG. 9A

PRINT QUALIFIED RECORDS

1. Check to include printing sections:
    a. Selection Criteria
    b. Statistic Results
    c. Data base Records - Check to include record fields
2. If "a" from step 1 is selected, format and write selection criterias to print file.
3. If "b" from step 1 is selected, format and write statistic results to print file.
4. If "c" from step 1 is selected,
    a. Start from first qualified record
    b. Format and write included field data to print file.
    c. Repeat step "b" until end of data file.
5. Print out print file.

FIG. 9B

## AUTOMATED WORKSTATION FOR THE MANUFACTURE OF OPTICAL FIBER COUPLERS

### BACKGROUND OF THE INVENTION

The present invention is related to manufacturing techniques for optical fiber couplers and, more specifically, to the automated manufacturing of such couplers.

Fiber optic couplers are used to connect optical fibers so that an optical, i.e., light, signal in a fiber passes to one or more fibers, or optical signals from several fibers pass to a single fiber. Networks of optical fibers with numerous couplers are being used with increasing frequency for the transmission of data, voice and video information due to the high transmission capacity of optical fibers, among other reasons.

In a typical coupler a single input fiber joins two output fibers to form a 1×2 coupler, or two input fibers join two output fibers to form a 2×2 coupler. Other combinations are possible. In a general manufacturing process of such couplers, two or more optical fibers having their outer coating removed are brought together and placed in contact with each other. The fibers may, or may not, be twisted together, depending upon the particular technique used to manufacture the coupler. The fibers are fused together by heat, as the fibers are placed under tension by slowly and carefully pulling them apart at a predetermined rate.

Heretofore, great care in handling the delicate fibers have been required by highly trained technicians with manual, or at best, semi-automated equipment. Thus the manufacturing costs for couplers are relatively high with production volumes low. This situation is an impediment to the desirable spread of fiber optic networks.

The present invention solves or substantially mitigates these problems with an automated workstation for fiber optic couplers.

### SUMMARY OF THE INVENTION

The present invention provides for a workstation for automatically manufacturing a coupler between at least two optical fibers. The workstation has a control unit for directing operations of said workstation and an operations unit for performing the manufacturing steps for the coupler. The operations unit has a pair of clamps for holding the optical fibers for the formation of a coupling region between the clamps, a torch for heating a predetermined length of the fibers between the clamps to fuse the fibers, motor assemblies responsive to the control unit for driving the clamps, a source laser block for generating an input signal into the optical fibers, and a laser measurement block which measures the signal from laser source block to determine characteristics of the coupling region between the optical fibers.

### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a perspective view of the workstation according to the present invention.

FIG. 2 is a block diagram illustrating the general organization of the workstation of FIG. 1.

FIG. 3 is a perspective and detailed view of part of operations unit of FIG. 1.

FIG. 4 is an cutaway view of a fiber clamp assembly of the operations unit of FIG. 1.

FIG. 5 is a detailed side view of the drive assembly of the fiber clamp of FIG. 4.

FIG. 6A is a block diagram of the laser source and measurement subsystem of the operations unit of FIG. 2; FIG. 6B shows the details of the laser measurement block of the subsystem of FIG. 6A; FIG. 6C details the adaptor fitting of an optical fiber to the photodiode in the block of FIG. 6B; and FIG. 6D illustrates the details and operation of the polarization controller block of the subsystem of FIG. 6A.

FIG. 7A is a block diagram of the input/output communication and control subsystem which is an interface between the linking optical fibers 12 and the operations unit 10; FIG. 7B is a block diagram of the interface between the linking optical fibers 12 and the control unit 11.

FIGS. 8A–8E list the programs which operate through the control unit 11 in pseudocode form.

FIGS. 9A–9B list the database programs which are used with the operation programs of FIGS. 8A–8E.

### DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

FIG. 1 shows a view of an automated workstation in accordance with the present invention. The workstation has an operations unit 10 and a control unit 11 in front of which an operator is seated. The operations unit 10 performs the steps to manufacture a coupler under the direction of the control unit 11, here represented by a display monitor 13. Through the control unit 11, the workstation may be programmed so that the different couplers with different parameters may be built.

The general organization of the operations unit 10 and the control unit 11 is represented in FIG. 2. The control unit 11, in the form of a personal computer, communicates with the operations unit 10 over two multimode optical fibers 12. The operations unit 10 has an input/output communication and control subsystem 20, a fiber clamp and drive subsystem 30, a heating and fusion subsystem 50, a laser source and measurement subsystem 70, a package and curing subsystem 80, and a process monitoring camera and display subsystem 90. It has been found that the electrical operations of the control unit 11 may disrupt the precise operations of the unit 10 and the optical link of the fibers 12 reduces the likelihood and effects of such electrical interference.

Parts of the operations unit 10, which are directly involved in the manufacture of couplers are shown in a cutaway and detailed view of FIG. 3. In FIG. 1 this part of the operations unit 10 lies under a transparent plastic covering 31 which protects a coupler from contaminants. FIG. 3 shows two clamps 31 of the fiber clamp subsystem 30 holding a pair of optical fibers, shown collectively by the reference numeral 100. The fibers 100 are held in each clamp 31 by vacuum. The clamps 31 move toward and away from each other during operation as indicated by arrows 24 and 25 respectively. A cover 23 protects the mechanism which drives the clamps 31.

A torch 51, part of the heating and fusion subsystem 50, provides the heat necessary for any fusing operation of the clamped fibers 100. The heating torch 51 is moved toward the fibers 100 for a fusion operation and moved away otherwise. Arrows 26 and 27 respectively illustrate the lateral and vertical motion of the torch 51. Also shown in FIG. 3 are a prepackage holder 81 of the package and curing subsystem 80. The holder 81 carries a prepackage into place against the fibers 100 so that epoxy placed on the fibers and prepackage may be cured by heaters within the holder 81. Arrows 28 and

29 respectively illustrate the horizontal and vertical movement of the prepackage holder 81 during its operation.

Finally, FIG. 3 shows a camera 91 of the process monitoring camera and display subsystem 90. The camera 91 allows a detailed view of the manufacturing process between the clamps 31.

FIG. 4 shows the details of the assembly for a fiber clamp 31. The clamps 31 are designed to hold the optical fibers 100 securely without damaging them and to provide a smooth and controlled pull on the fibers 100 in the coupler manufacturing process. The assembly has a base 45 with a channel 46 for the vacuum to clamp the optical fibers, here shown as two separate fibers 100A and 100B. The channel within the base 45 communicates with a flexible tube 44 which has an end fixed to the base 45. The other end of the flexible tube 44 is connected to a vacuum pump (not shown). A vacuum distribution plate 42 rests on the top flat surface of the base 45. The plate 42 has a linearly arranged series of holes 43 which communicate with the channel 46. A pair of clamp surface plates 40 lie on the plate 42 and are fixed to the base 45 by machine screws 41 which fit through holes in the plates 40 and 42. Each plate 40 has a beveled upper surface 40A which leads to a plate edge 40B. The two plates 40 are mounted so that the edges 40B are positioned parallel to each other over the holes 43 of the distribution plate 42. The edges 40B are slightly separated from each other to form a linear and beveled opening which receives optic fibers 100A and 100B. The air pressure from the vacuum in the channel 46 through the holes 43 holds the fiber 100 in place. To provide an alignment reference for the plates 40, a side plate 49 is mounted to the base 45. One of the plates 40 is mounted against the side plate 49 to fix the location of its edge 40B and the edge 40B of the second plate 40 can then be located.

The bottom of the clamp assembly has a carriage base 47 upon which the base 45 is mounted. A bearing surface 48 is fixed along the bottom edge of carriage base 47. A second bearing surface 59 is attached to the housing 55 for the clamps 31. To ensure that the two races 48 and 59 slide easily past each other, a thin bearing plate 56 with apertures holding cylinder roller bearings 57 is placed between the races. It should be understood that there is a similar arrangement of bearing surfaces and bearings on the other side of the carriage base 47 to form parallel races for the clamps 31. This permits each clamp 31 to slide back and forth as indicated in FIG. 3.

FIG. 5 shows the details of the drive assembly for each of the clamps 31. A stepper motor 32, mounted to the housing 55, has a shaft 33 which is connected through a coupling 34 to a reduction gear box 35. The gear box 35, mounted to the housing, has a drive screw 36 with a journal at the far end which is held in place by a support 38, also fixed to the housing, containing a journal bearing. Note that the support 38 also receives a drive screw 36 for the second clamp 31. Mounted on the drive screw 36 is a drive screw carriage 37, which moves along the drive screw 36 backward or forward, depending upon the direction of the rotation of the motor 32. The drive screw carriage 37 has an arm which extends upward toward the assembly for the clamp 31. The carriage base 47 of the clamp assembly has a clamp undercarriage 58 which has an arm which extends downward toward the drive screw carriage 37. The arms of the drive screw carriage 37 and the clamp undercarriage 49 are connected by a coupling linkage 39. Thus as the drive screw 36 turns, the clamp 31 moves back and forward.

Also pictured in FIG. 5 a front view of the torch 51 and the prepackage holder 81. The torch 51 is made from a machinable glass ceramic. Torches made from metal are required to be shut off after a fusing operation to prevent the heat buildup from melting the torch itself. Additionally the cycling of the torch as it is turned off and on causes contaminating particles to be generated. The torch 51 can be maintained in an ignited state during the manufacture of fiber optic couplers so that the fusing of optical fibers can be performed uniformly and reliably. The torch is also shaped and dimensioned for specific manufacturing requirements for a optical fiber coupler. One such torch, which is also useful for automated workstations, is described in U.S. patent Ser. No. 08/004,041, entitled, "A TORCH FOR MANUFACTURE OF OPTICAL FIBER COUPLERS AND METHOD OF MANUFACTURE," filed Jan. 15, 1993 by J. J. Pan et al and assigned to the present assignee.

FIG. 3 shows the torch 51, its flexible gas supply tube 52 and a control valve 53. The control valve 53 is connected to a source (not shown) of gas, typically hydrogen, so that gas is supplied through the tube 52 to the torch 51. Also associated with the heating and fusion subsystem 50 is a safety gas sensor 54 which is coupled to the control valve 53. The gas sensor, such as Part No. 2001-00, from Sierra Monitor Corporation of Milpitas, California, detects the presence of gas. If the concentration of gas exceeds a predetermined level, the sensor activates an alarm and emits a signal to the valve 53 to shut off the gas supply. Note that the drive mechanism for the torch 51 is not shown since the design of such a mechanism is a straightforward matter.

Likewise the drive mechanism for the prepackage holder 81 is not shown. The holder 81 is trough-shaped, into which fits a prepackage, a glass half-tube. Normally the holder 81 rests out of the way below the clamps 31 and fibers 100. For a packaging operation the holder 81 rises to set a prepackage in slight contact with the fibers 100 between the clamps 31. Electric heating elements in the metal holder 81 help cure epoxy used on the fibers 100 and prepackage.

The process monitoring camera and display subsystem 90, which has the video camera 91, with a microscope lens, connected to the monitor 92. The camera 91 is focused upon the coupling region of the coupler to be formed between the clamps 31, as shown in FIG. 3. The camera 91 allows an operator to observe the minute details of the formation of the coupler during the manufacturing process on the monitor 92.

FIG. 6A shows the organization of the laser source and measurement subsystem 70, which has a laser source block 71, a laser measurement block 72, and a polarization controller block 73. The laser source block 71 has a Fabry-Perot laser diode unit having an output connected to a fitting 73. Laser diodes units of 850 nm, 1300 nm, 1310 and 1550 nm wavelengths may be used for a desired optical wavelength. The output from the laser source block 71 is sent by an optical fiber to the polarization controller block 73. As the name implies, the block 73 controls the state of polarization of the optical signal from the laser source block 71. The output signal from the block 73 is connected by optical fiber to a connector fitting 74.

The laser measurement block 72 measures the strength of an optical signal received through a connec-

tor fitting 75, which is mounted to the front of the workstation. See FIG. 1. As shown in FIG. 6B, light from the fitting 75 is directed toward a photodiode 77. FIG. 6C illustrates the bare fiber adaptor used to hold the end of the optical fiber connected to the fitting 75 in place with respect to the photodiode 77. The output terminals of the photodiode 77 are connected to the input terminals of an operational amplifier 78. By setting the magnitude of the resistance between the output terminal and the negative input terminal of the amplifier 78, as represented by a programmable resistance block 76, the amplification factor for the output of the photodiode 77 may be selected. The design of circuits having resistances which may be set or programmed are well known to circuit designers.

The polarization controller 73 is formed by an optical fiber which receives the light from the laser source block 71. The fiber is coiled by two plates 76, one of which holds a quarterwave coil and the other plate holds a halfwave coil, as shown in FIG. 6D. The amount of mechanical rotation of the plates 76 about an axis in the plane of the coils is translated into a rotation angle of polarization of the light being emitted from the laser source. A description of this type of polarization controller is found in, "In-line single-mode fiber polarization controllers at 1.55, 1.30, and 0.63 $\mu$m," by Birgit G. Koehler and John E. Bowers, *Applied Optics*, vol. 24, no. 3, Feb. 1, 1985, pp. 349–353. During a test of a coupler being manufactured, the plates 76 are rotated about a wide arc by a motor (not shown) to test the change in the coupling ratio of the coupler with respect to the polarization of light passing through the coupler. The amount of light received by the photodiode 77 of the light measurement block 72 with respect to the rotation of the plates 76 yields the sensitivity of the manufactured coupler to the polarization of light.

FIG. 1 illustrates how the laser source and measurement subsystem 70 is connected during the manufacture of a coupler. One end of the optical fibers 100 is terminated with a connector which is inserted into the output fitting 74 of laser source and measurement subsystem 70. Note that the fiber is coiled by a supply spool 101. Another end of the optical fibers 100 is terminated with a connector which is inserted into the fitting 75. Thus, optical signals on this fiber 100, say 100A, are received by the photodetector 77. The output signal of the photodetector may be amplified by a selectable factor to monitor the signal on the fiber 100A. As shown in the drawing, there are multiple fittings 74 and 75 so that each fiber of the manufactured coupler can be supplied and measured with light.

Referring to FIG. 2, the input/output communication and control subsystem 20, a conduit through which the control unit 11 controls the subsystems of the operations unit 10 and receives information from them, is in the form of an adaptor card which is interfaced between the optical fibers 12 and the rest of the operations unit 10. The subsystem 20 translates light signals from one of the fibers 12 into electrical signals for the unit 10 and electrical signals generated in the unit 10 into optical signals for the other of the two fibers 12. In this manner, all of the subsystems 30, 50, 70, 80 and 90 communicate with the control unit 11.

FIG. 7A details the subsystem 20. Light signals are received by a fiber optic receiver 21 from one of the fibers 12 and transmitted by a fiber optic transmitter 22 to the other fiber 12. Transmission and reception occurs at a 72 Mbps data rate over these fibers 12. Part no. ODL70 from AT&T Microelectronics, Inc. of Allentown, Pa. is used for the receiver 21 and transmitter 22. The serial electrical signals, translated from the light signals by the receiver 21, are changed into parallel signals by a serial-to-parallel communication circuit 23, a TAXI integrated circuit from Advanced Micro Devices, Inc. of Sunnyvale, Calif. The parallel signals are sent to a communication control gate array 25, part no. TPC1010A from Texas Instruments, Inc. of Dallas, Tex. The array is organized into a command interpreter & error handling unit 25A, a unit 25B of data latches and registers 25B and an address decoder unit 25C. The data latch and register unit 25B is connected by bidirectional data paths to the command interpreter & error handling unit 25A and is also connected to the decoder unit 25C. The unit 25A receives signals from the serial-to-parallel communication circuit 23 and passes control signals to an input/output control portion of the backplane bus 27 of the operations unit 10 through driver circuits 26. The data latch and register unit 25B also receive signals from the serial-to-parallel communication circuit 23 and sends data signals through the driver circuits 26 to the data portion of the backplane bus 27. The address decoder unit 25C sends address signals to the address portion of the bus 27 through the driver circuit 26. The driver circuit 26 is formed by a standard parallel driver integrated circuit. Such circuits are supplied by many semiconductor companies. For completeness' sake, the backplane bus 27 is also shown with power and ground lines.

Communication from the unit 10 to the fiber 12 is performed from the input/output control and the data portions of the backplane bus 27 through the driver circuit 26 to the command interpreter & error handling unit 25A and the data latch and register unit 25B respectively. Both units 25A and 25B are connected to a parallel-to-serial communication circuit 24, another TAXI integrated circuit from Advanced Micro Devices, Inc. The serial signals from the circuit 24 are send to the fiber optic transmitter 22 for transmission on the fiber 12.

The communication control gate array 25 is formed by programming various different integrated circuits, which are now available to a electrical system designer. Besides the part from Texas Instruments, other circuits which may be used for the gate array 25 include Programmable Array Logic integrated circuits, such as a 22V10 from Advanced Micro Devices, and a Field programmable Gate Array from Actel, Inc. of Sunnyvale, Calif.

The control unit 11 likewise requires an interface unit to the fiber 12 for communication to the operations unit 10. FIG. 7B shows the organization of the interface unit to the fiber 12. Except for the reversal of some of the signal paths, it is nearly identical to that shown in FIG. 7A. Hence, no further explanation is made for the interface unit.

The control unit 11 is an IBM-type personal computer with a special interface to the operational unit 11, as explained previously. The control unit 11 has a central processing unit, an 80486 microprocessor from Intel Corporation of Santa Clara, Calif., two floppy disk drives, a hard disk drive, a monitor, a video acceleration card for the Windows computer program discussed below, a keyboard, and a mouse, all of which interface on a bus. This type of computer with these components are commonly available. Also connected to the bus is a specially designed fiber optic interface unit in the form

of an adaptor card for the optical fiber 12 to the operational unit 10.

The operating system program of the control unit 11 is the common combination of MS-DOS, version 5.0, and Wind ws, version 3.1, both from Microsoft Corporation of Redmond, Wash. The Windows program provides a graphical user interface which permits the user to easily operate the workstation. Other operating systems could be used, whether custom or commercially available.

Under the operating system are the applications programs which direct the operations unit 10. Each applications program is designed for a particular type of fiber optic coupler. Within the program there is parameter selection, such as coupling ratio, insertion loss and wavelength, which allows a coupler to be adapted for a particular use.

Before the workstation is engaged, however, the fibers are first prepared. The protective jacket is removed from the section of the fibers where the coupler is to be formed. Any fibers which must be pretapered are heated and stretched on the workstation. Then the steps for manufacturing the coupler itself are started. After the vacuum to the clamps 31 is turned on to hold a predetermined number of fibers 100 in place, the clamps 31 are driven apart to pull on the fibers 100 in a controlled manner. The tension on the fibers 100 affects the power coupling ratio of the coupler being formed. The coupling ratio is monitored by the strength of the optical signal to the photodiode 77. When the specified coupling ratio is reached, the clamps 31 stop and maintain the fibers 99 in place. The torch 51, which has been ignited, moves forward and heats a portion of the fibers to fuse them together.

A prepackage, a half-cylindrical tube, is manually placed into the pre-packing holder 81. The vacuum to the holder 81 is turned on and the holder 81 moves to the fibers 100 so that the prepackage holds the fibers 100. Thermal epoxy is applied at the two ends of the tube. The heating element in the holder 81 is turned on for a specified amount of time to cure the epoxy. The vacuum to the holder 81 is turned off and the polarization test is performed.

After the polarization test, the vacuum to the clamps 31 is turned off and the coupler in its prepacking tube is manually removed from the workstation for the final packaging steps. Finally, the workstation reinitializes itself to return all parts, such as the clamps 31, to the initial state to begin the manufacturing cycle over again.

In the workstation each of these operational steps are performed automatically. FIGS. 8A-8E display the operational steps for manufacturing a fiber optic coupler in the described workstation in pseudocode form. The workstation starts with the Fabrication Program in FIG. 8A which initializes the workstation. The term, PD, refers to the photodetector 77; the term, CR, to the coupling ratio, i.e., the ratio of the amount of light in an output fiber of the manufactured coupler to the amount of light in an input fiber of the coupler; and the term, EL, refers to excess loss, the amount of light which lost after passing through the coupler. The pulling motor refers to the motor which drives the vacuum clamps 31. Finally the buttons referred to are displays of buttons, or icons, in the terminology of the Windows operating system, by which other programs are started, or launched, when "clicked" by the arrow cursor.

These programs, or operation buttons, are described below. RECAL recalibrates the clamp motor positions. The "database" referred to is discussed below. HOME moves the clamps 31 and prepackaging holder 81 into starting position. PPULL places the torch 51 into a ready position as the clamps 31 move away from each other a predetermined amount. PULL moves the torch 51 into position and the clamps 31 are moved apart. The PULL++ program moves the clamps 31 apart by a predetermined amount. PACK is the packaging program by which the holder 81 moves into position. In DEPACK the vacuum of the holder 81 is turned off and returned to its home position. PST is the polarization test program. The program rotates the quarterwave plates 76 of the controller 73 as the output of the photodiode 77 (PD) is recorded for each step of the rotation. A polarization value is obtained by the maximum deviation of the coupling ratios for all the steps of rotation. A special NEXT button, whose pseudocode is shown in FIG. 8C, is defined to further simplify operations. For a routine process the NEXT button ensures the correct procedure to follow and thereby maintains high production yields. The ZERO program records the offsets for the photodiode 77. The offsets are used to calibrate the photodiode 77. The STOP button stops the current operation and, depending upon the operation, moves to a different one, as indicated in FIG. 8D, before returning to the Fabrication Program. The EXIT button quits the Fabrication Program.

The Fabrication Program also has other groups of buttons, including Vacuum Buttons and Heater Buttons. The Vacuum Buttons include a PULL LEFT button which toggles the vacuum of the left clamp 31 off and on, and a PACKAGE button, which toggles the vacuum of the prepackage holder 81 off and on. The Heater Buttons include an ON/OFF button which toggles the heater of the holder 81 off and on, and an AUTO button, which turns off the heater of the holder 81 for a predetermined amount of curing of epoxy on the prepackage.

It should be noted that the steps described above are for the general manufacture of a fiber optic coupler. The details in preparing the fibers 100 and in arranging them before loading into the clamps 31 all contribute to the performance of the finished coupler. For example, an explanation of a particular 2×2 coupler is found in U.S. patent Ser. No. 08/004,043, entitled, "BROAD BANDWIDTH, SINGLE-MODE FIBER OPTIC COUPLER AND METHOD OF MANUFACTURE THEREFOR," filed Jan. 15, 1993 by J. J. Pan et al. and assigned to the present assignee. The workstation according to the present invention permits the steps of clamping, heating, pulling, fusing, and prepackaging the coupler to be precisely specified for the optimum performance of the desired coupler for automated execution.

The control unit 11 also collects data from the manufacturing process into a database. From the specified records and fields of the database, information, such as yield, quality distribution, productivity, and diagnostics, are provided for the manufactured coupler units. FIG. 9A-9B describes the database program which collects the manufacturing data in pseudocode form. The Fabrication Data file shows the fields of records in that file. The Qualified Records Data file is another data file, which is used to help set aside records in the Fabrication Data file. The Statistical Analysis file performs the requested analysis of the manufactured couplers from the Fabrication Data file. The Display Qualified Records file and Print Qualified Records file respec-

tively display and print out the records from the Qualified Records Data file.

Thus with the described workstation, high volumes of high quality, highly reliable fiber optic couplers may be manufactured at low cost. The precision of the operation of the workstation permits couplers to be manufactured with high yields and the programmability of the workstation allows operations to be performed with flexibility and ease.

While the above is a complete description of the preferred embodiments of the present invention, various alternative, modifications and equivalents may be used. It should be evident that the present invention is equally applicable by making appropriate modifications to the embodiments described above. Therefore, the above description should not be taken as limiting the scope of the invention which is defined by the metes and bounds of the appended claims.

What is claimed is:

1. A workstation for automatically forming a coupling region between at least two optical fibers, said workstation comprising

control means for directing operations of said workstation;

a pair of clamps for holding said optical fibers for the formation of said coupling region between said clamps;

means responsive to said control means for heating a predetermined length of said fibers between said clamps to fuse said length;

means responsive to said control means for driving said clamps;

means responsive to said control means for generating a selectable input signal into said optical fibers; and

means for monitoring an output signal responsive to said input signal to determine characteristics of said coupling region between said optical fibers;

whereby fiber optic couplers are automatically manufactured.

2. The workstation as in claim 1 further comprising means responsive to said control means for positioning and holding a package for said coupling region fibers,

3. The workstation as in claim 2 wherein said positioning and holding means further comprises means for heating said package for thermally curing epoxy;

4. The workstation as in claim 1 further comprising means for recording monitored output signals and determined characteristics for each fiber optic coupler manufactured,

5. The workstation as in claim 4 further comprising means for placing said monitored output signals and determined characteristics into records and fields to form a database of said manufactured fiber optic couplers.

6. The workstation as in claim 5 further comprising means for calculating statistical data from said records and fields for said manufactured fiber optic couplers.

7. The workstation as in claim 1 wherein said control means is physically separated from said operations area.

8. The workstation as in claim 7 wherein said control means communicates with said operations area by an optical fiber.

9. The workstation as in claim 1 wherein said heating means comprises a torch connected to a gas supply and further comprising means for detecting a gas concentration over a predetermined amount.

10. The workstation as in claim 9 further comprising means responsive to said detecting means for turning off said gas supply.

11. A method of automatically manufacturing a fiber optic coupler of at least two optical fibers, said method comprising

defining operational parameters for said fiber coupler;

mounting on a pair of clamps a prepared section of said optical fibers for a coupling region with said coupling region therebetween;

heating a section of said optical fibers to fuse said fibers together responsive to said defined operational parameters;

driving said clamps apart responsive to said defined operational parameters;;

generating an input signal into said optical fibers, said input signal selected by said defined operational parameters;

monitoring an output signal responsive to said input signal as said clamps are driven apart to determine at least one operational parameter;

stopping said clamps when said one operational parameter matches a defined operational parameter;

whereby a fiber optic coupler is manufactured by automation.

12. The method as in claim 11 further comprising automatically positioning and holding a package for said coupling region of said fibers after said stopping step.

13. The method as in claim 12 further comprising heating said package for thermally curing epoxy after said positioning and holding step.

14. The method as in claim 11 comprising recording monitored output signals and determined characteristics for each fiber optic coupler manufactured.

15. The method as in claim 14 placing said monitored output signals and determined characteristics into records and fields to form a database of said manufactured fiber optic couplers.

16. The method as in claim 15 further comprising calculating statistical data from said records and fields for said manufactured fiber optic couplers.

17. The method as in claim 11 wherein said control means is physically separated from said operations area.

18. The method as in claim 17 wherein said control means communicates with said operations area by an optical fiber.

19. The method as in claim 11 wherein said heating step comprises using a torch connected to a gas supply and said method further comprises detecting a gas concentration over a predetermined amount.

20. The method as in claim 19 further comprises turning off said gas supply responsive to said detecting step.

* * * * *

US-PAT-NO: 5861970

DOCUMENT-IDENTIFIER: US 5861970 A

TITLE: Dispersion compensation in an optical communications system

---------- KWIC ---------

Brief Summary Text - BSTX (9):

In a second, known dispersion compensation technique a negative dispersion optical fibre is employed to compensate either at the transmission end, or at the receiver end of the optical link for the positive dispersion suffered by optical signals propagating along the transmission optical fibre. When optical signals at 1.55 .mu.m are transmitted along a transmission optical fibre having a dispersion zero at 1.31 .mu.m, the signals will suffer positive dispersion i.e. the sign of the differential of their group delay with wavelength, will be positive, and will typically be of the order of 17 ps/km/nm. Single mode optical fibre can be specifically designed to have a large negative chromatic dispersion, by choosing the waveguide parameters to give large negative waveguide dispersion, for example a fibre having a core of small diameter and high refractive index will have negative waveguide dispersion. Such a scheme was employed by Izadpanah et al in "Dispersion Compensation In 1310 nm Optimised SMFs Using Optical Equaliser Fibre, EDFAs And 1310/1550 nm WDM" Electronics Letters, 16 Jul. 1992, volume 28, no. 15, page 1469. Izadpanah et al employed a specially designed negative dispersion fibre having a dispersion of -45 ps/km/nm. The length of negative dispersion fibre required was approximately one third of the length of the transmission link over which dispersion was being compensated. Such large lengths of additional fibre are clearly inconvenient and expensive. Furthermore due to the high level of doping used in the core, and the small core size this fibre had a relatively high loss, so that amplification of the optical signal is essential, even if the bit rate of the system is not increased.

Claims Text - CLTX (23):
17. An optical communications system as claimed in claim 16, wherein said semiconductor device Is a distributed feedback laser.

US005861970A

# United States Patent [19]

**Tatham et al.**

[11] **Patent Number: 5,861,970**

[45] **Date of Patent: Jan. 19, 1999**

[54] **DISPERSION COMPENSATION IN AN OPTICAL COMMUNICATIONS SYSTEM**

[75] Inventors: **Martin Christopher Tatham**; **Gerard Sherlock**, both of Suffolk, United Kingdom

[73] Assignee: **British Telecommunications public limited company**, London, United Kingdom

[21] Appl. No.: **586,634**

[22] PCT Filed: **Mar. 23, 1994**

[86] PCT No.: **PCT/GB94/00602**

§ 371 Date: **Jan. 29, 1996**

§ 102(e) Date: **Jan. 29, 1996**

[87] PCT Pub. No.: **WO95/03653**

PCT Pub. Date: **Feb. 2, 1995**

[30] **Foreign Application Priority Data**

Jul. 20, 1993 [GB] United Kingdom ................ 9315011.8

[51] **Int. Cl.**[6] .................................................... **H04B 10/00**

[52] **U.S. Cl.** .......................... **359/161**; 359/134; 359/160; 359/173; 359/179

[58] **Field of Search** .................................... 359/134, 160, 359/161, 173, 179, 188, 195, 341; 372/6; 330/59, 308

[56] **References Cited**

U.S. PATENT DOCUMENTS

5,365,362 11/1994 Gnauck et al. ......................... 359/161

FOREIGN PATENT DOCUMENTS

0314373 5/1989 European Pat. Off. ............... 359/161
4081724 3/1992 Japan .

OTHER PUBLICATIONS

Yazaki et al, "Chirping Compensation Using a Two–Section Semiconductor Laser Amplifier", Journal of Lightwave Technology, vol. 10, No. 9, Sep. 1992, New York, US, pp. 1247–1254.

Patent Abstracts of Japan, vol. 16, No. 301 (P–1379) 3 Jul. 1992 & JP A 04 081 724 (NEC).

*Primary Examiner*—Kinfe-Michael Negash
*Attorney, Agent, or Firm*—Nixon & Vanderhye P.C.

[57] **ABSTRACT**

A method of compensating for dispersion in an optical communications system includes the steps of: positioning a semiconductor optical amplifier between a first and a second length of optical fibre, launching optical signals into the first length of optical fibre, directing optical signals emerging from the first length of optical fibre into the semiconductor optical amplifier, supplying optical pump radiation to the semiconductor optical amplifier so that the optidcal signals and the pump radiation interact within the semiconductor optical amplifier and generate the phase conjugate of the optical signals, and launching the phase conjugate optical signals into the second length of optical fibre.

**20 Claims, 11 Drawing Sheets**

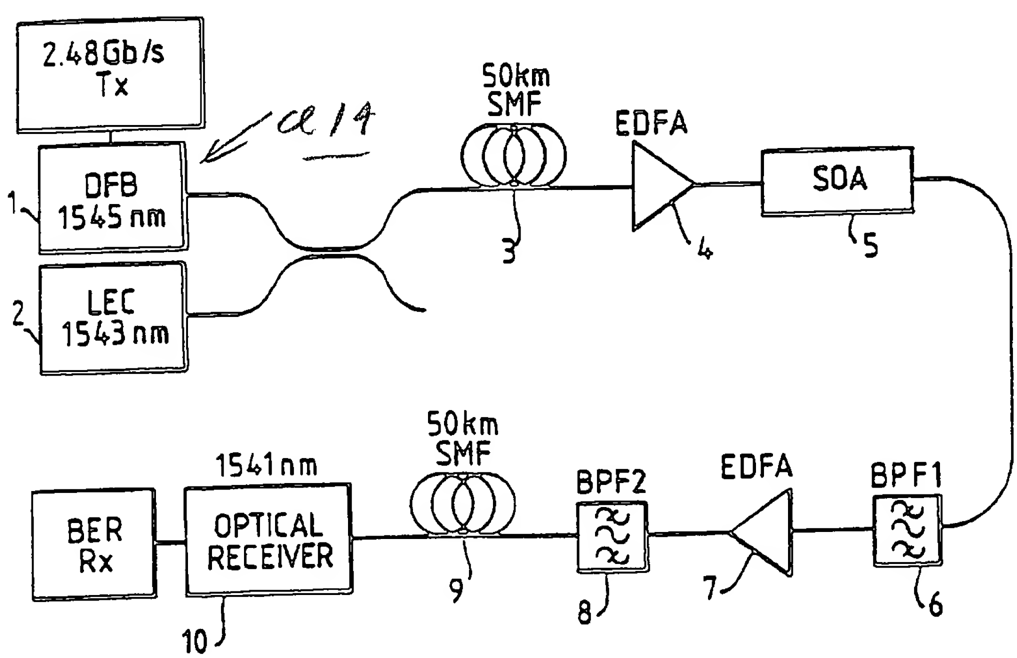


Fig. 1a

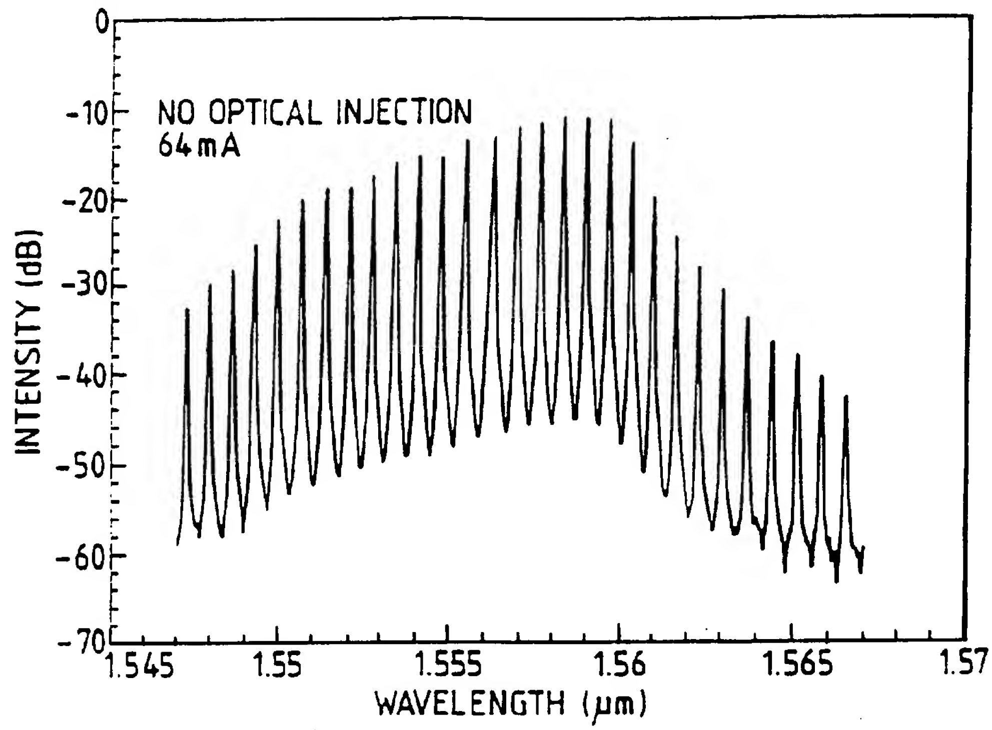

NO OPTICAL INJECTION
64mA
INTENSITY (dB)
0
-10
-20
-30
-40
-50
-60
-70
1.545
1.55
1.555
1.56
1.565
1.57
WAVELENGTH (μm)

Fig. 1b

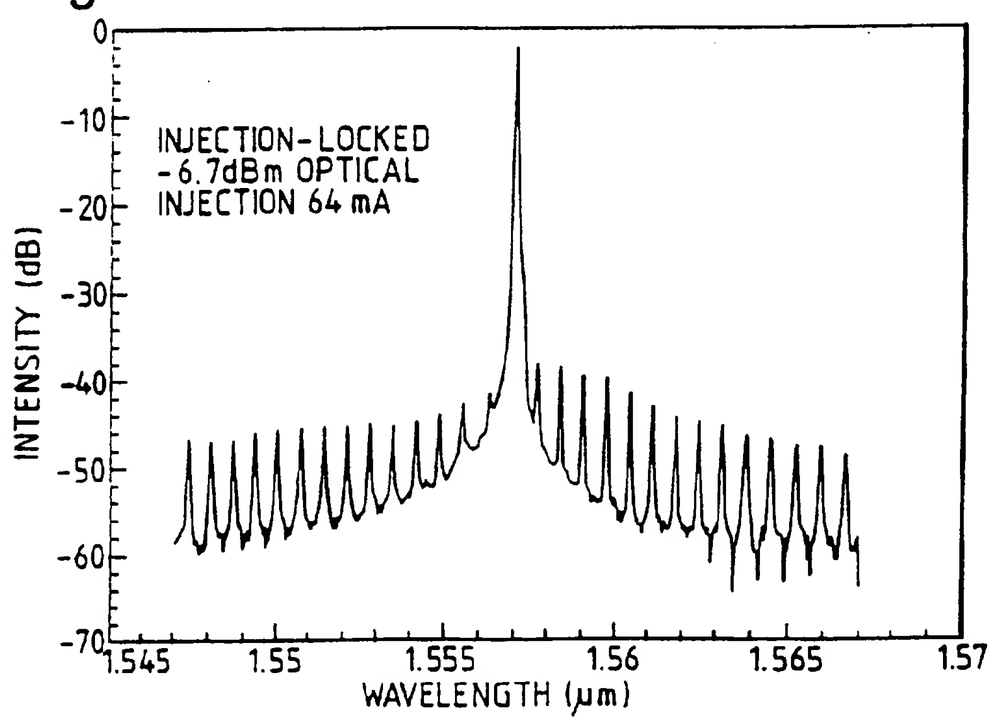

INJECTION-LOCKED
-6.7dBm OPTICAL
INJECTION 64 mA
INTENSITY (dB)
0
-10
-20
-30
-40
-50
-60
-70
1.545
1.55
1.555
1.56
1.565
1.57
WAVELENGTH (μm)

Fig. 2a

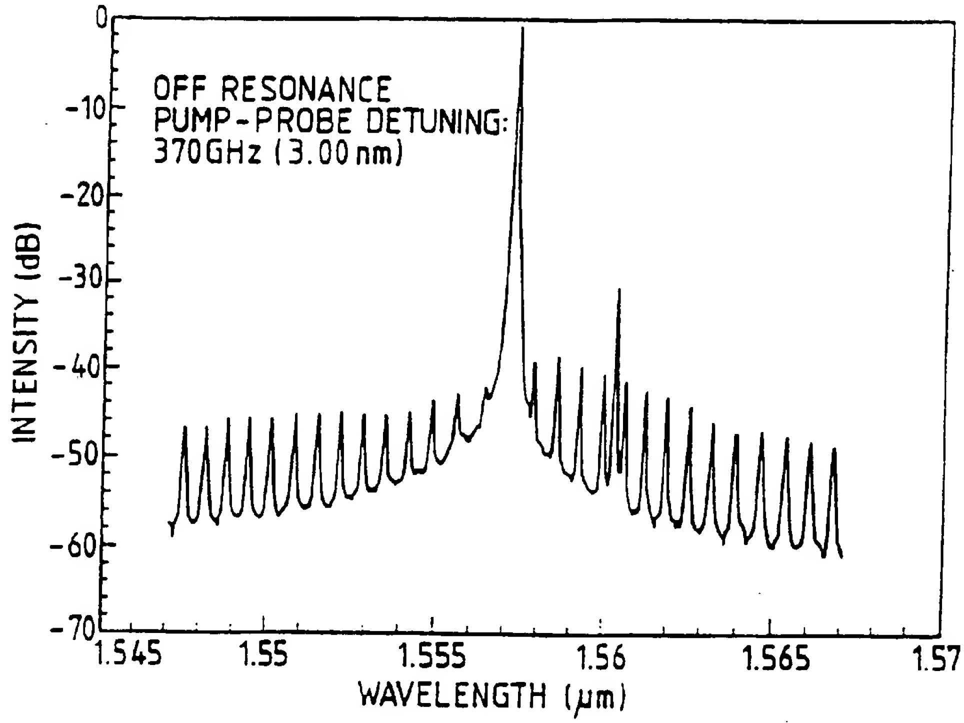

0
-10
-20
-30
-40
-50
-60
-70
INTENSITY (dB)
OFF RESONANCE
PUMP-PROBE DETUNING:
370GHz (3.00nm)
1.545
1.55
1.555
1.56
1.565
1.57
WAVELENGTH (μm)

Fig. 2b

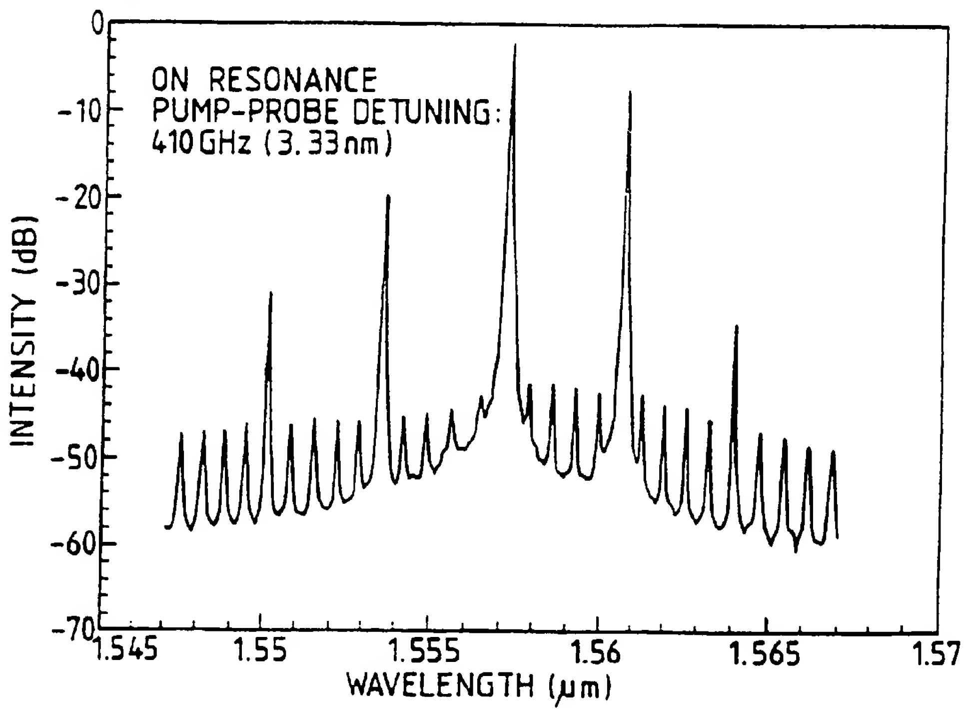

0
-10
-20
-30
-40
-50
-60
-70
INTENSITY (dB)
ON RESONANCE
PUMP-PROBE DETUNING:
410GHz (3.33nm)
1.545
1.55
1.555
1.56
1.565
1.57
WAVELENGTH (μm)

*Fig. 3a*

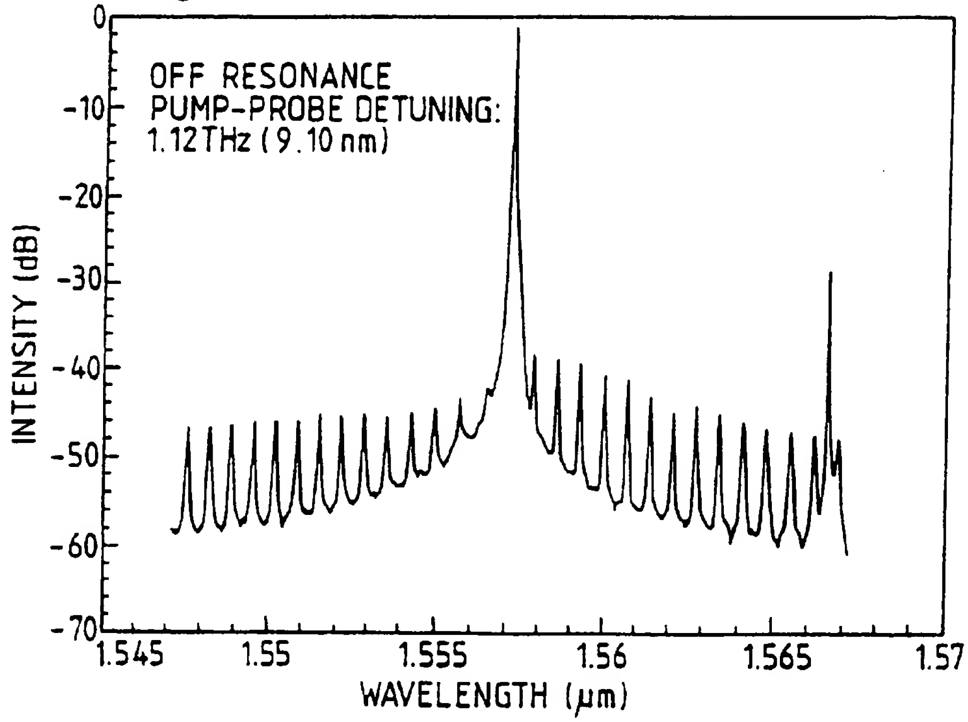

OFF RESONANCE
PUMP-PROBE DETUNING:
1.12THz (9.10 nm)
INTENSITY (dB)
0
-10
-20
-30
-40
-50
-60
-70
1.545
1.55
1.555
1.56
1.565
1.57
WAVELENGTH (μm)

*Fig. 3b*

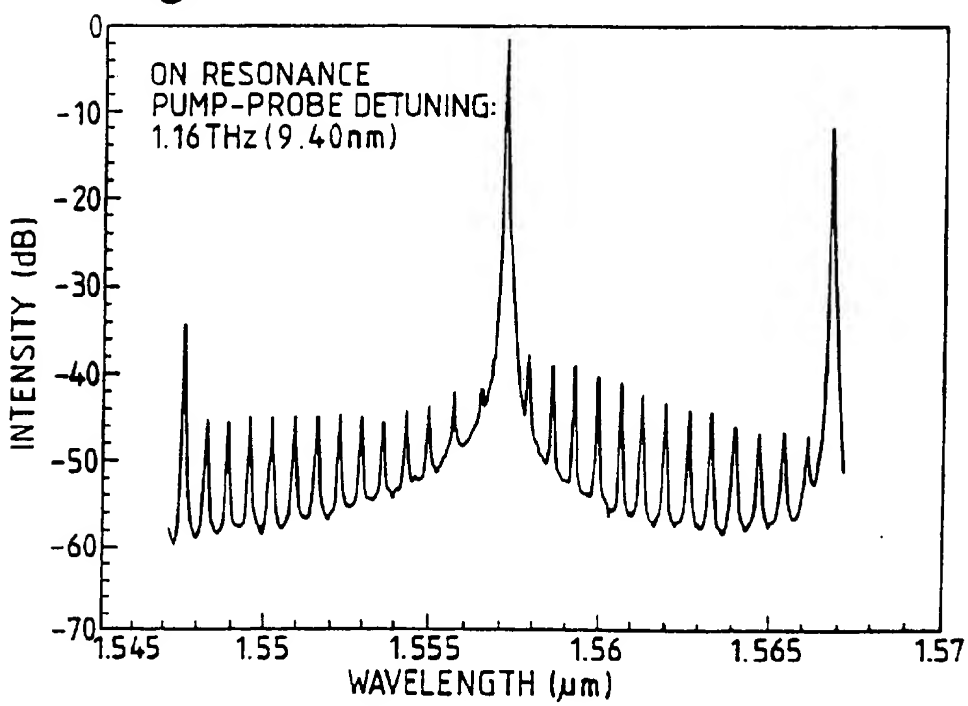

ON RESONANCE
PUMP-PROBE DETUNING:
1.16THz (9.40nm)
INTENSITY (dB)
0
-10
-20
-30
-40
-50
-60
-70
1.545
1.55
1.555
1.56
1.565
1.57
WAVELENGTH (μm)

*Fig. 4a*

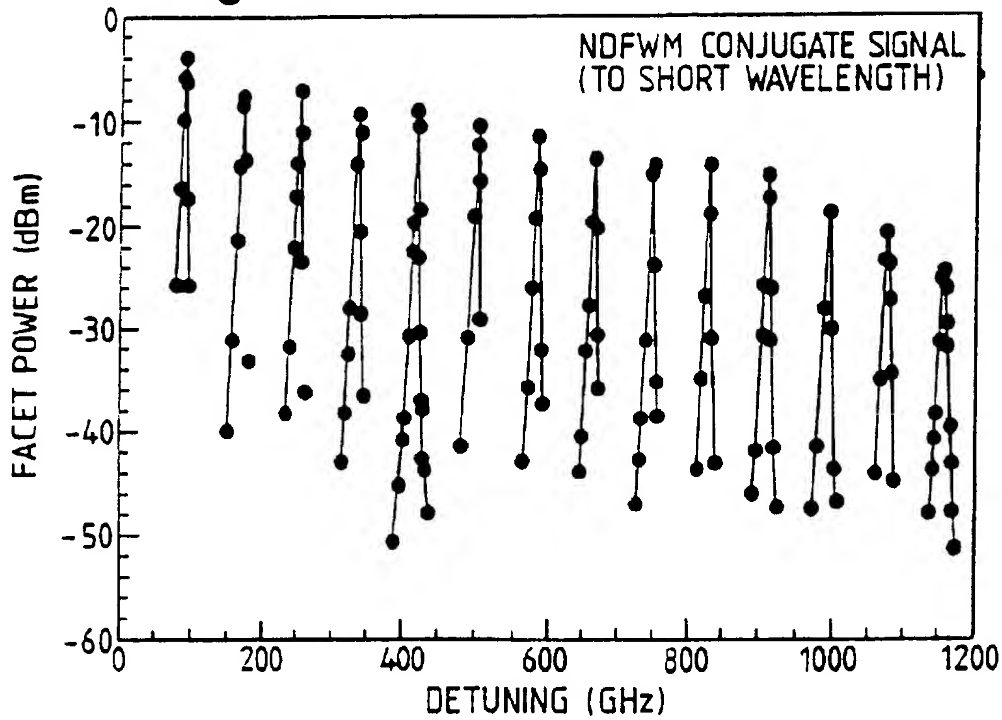

NDFWM CONJUGATE SIGNAL
(TO SHORT WAVELENGTH)
FACET POWER (dBm)
0
-10
-20
-30
-40
-50
-60
0
200
400
600
800
1000
1200
DETUNING (GHz)

*Fig. 4b*

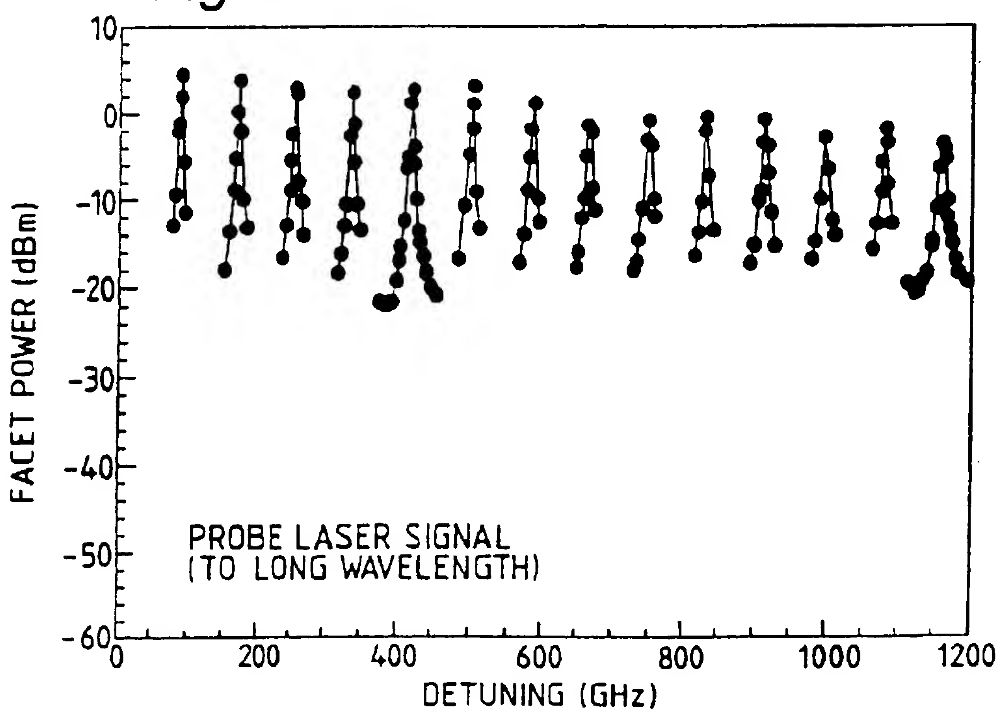
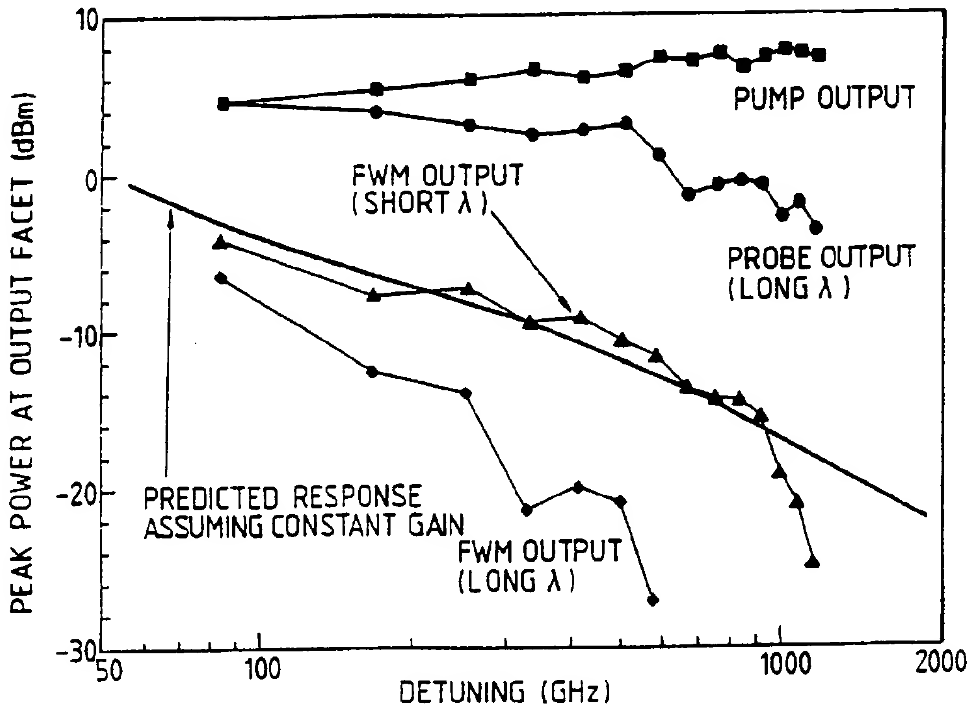
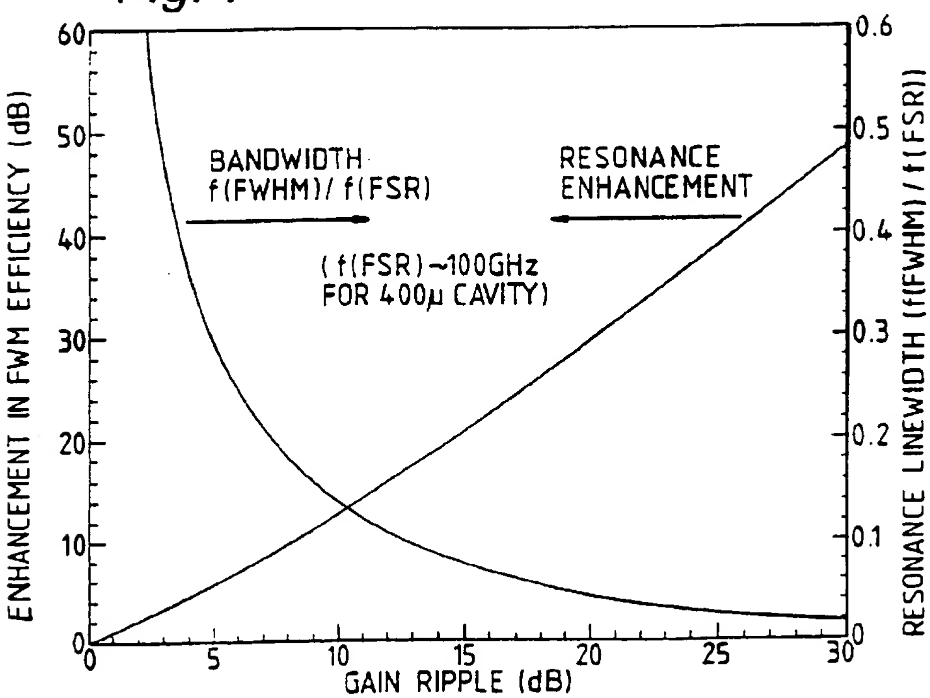

PROBE LASER SIGNAL
(TO LONG WAVELENGTH)
FACET POWER (dBm)
10
0
-10
-20
-30
-40
-50
-60
0
200
400
600
800
1000
1200
DETUNING (GHz)

Fig. 5



PEAK POWER AT OUTPUT FACET (dBm)
10
0
-10
-20
-30
50
100
1000
2000
DETUNING (GHz)
PUMP OUTPUT
PROBE OUTPUT
(LONG λ)
FWM OUTPUT
(SHORT λ)
PREDICTED RESPONSE
ASSUMING CONSTANT GAIN
FWM OUTPUT
(LONG λ)


Fig. 7



ENHANCEMENT IN FWM EFFICIENCY (dB)
60
50
40
30
20
10
0
0.6
0.5
0.4
0.3
0.2
0.1
0
RESONANCE LINEWIDTH (f(FWHM)/f(FSR))
BANDWIDTH
f(FWHM)/f(FSR)
RESONANCE
ENHANCEMENT
(f(FSR)~100GHz
FOR 400μ CAVITY)
0
5
10
15
20
25
30
GAIN RIPPLE (dB)

Fig. 6a

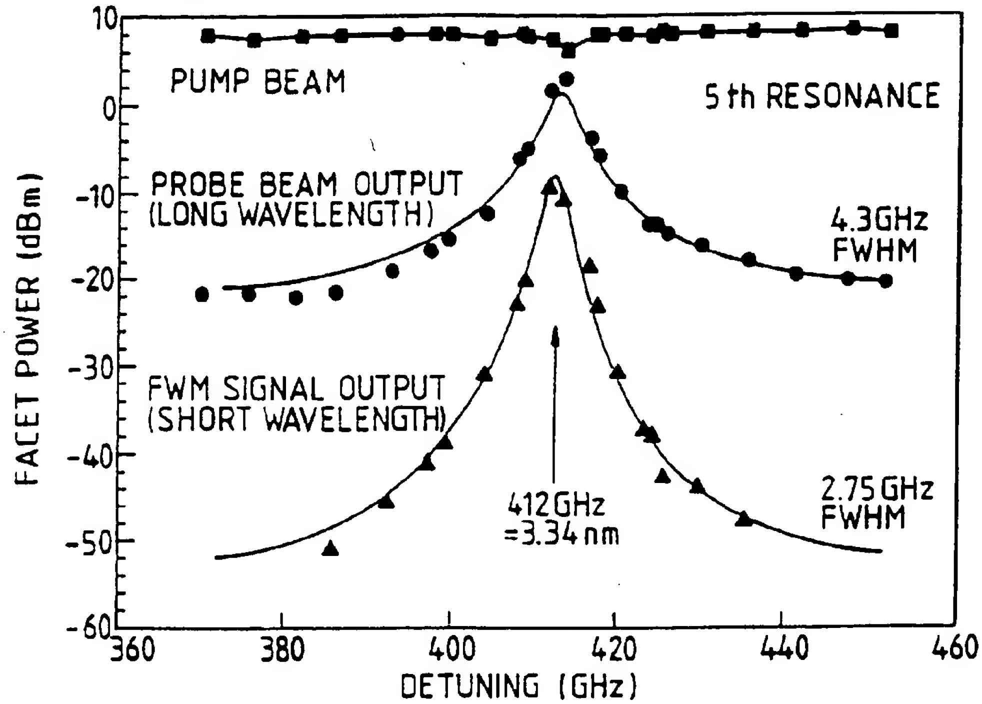

10
0
-10
-20
-30
-40
-50
-60
FACET POWER (dBm)
PUMP BEAM
5th RESONANCE
PROBE BEAM OUTPUT
(LONG WAVELENGTH)
4.3GHz
FWHM
FWM SIGNAL OUTPUT
(SHORT WAVELENGTH)
412GHz
=3.34nm
2.75GHz
FWHM
360
380
400
420
440
460
DETUNING (GHz)

Fig. 6b

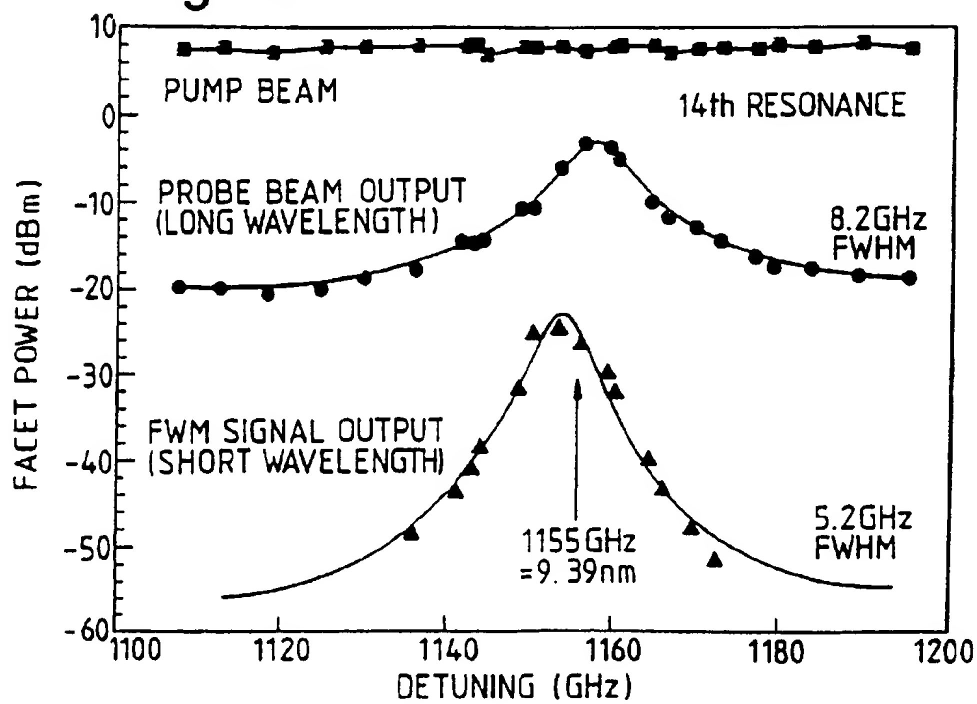

10
0
-10
-20
-30
-40
-50
-60
FACET POWER (dBm)
PUMP BEAM
14th RESONANCE
PROBE BEAM OUTPUT
(LONG WAVELENGTH)
8.2GHz
FWHM
FWM SIGNAL OUTPUT
(SHORT WAVELENGTH)
1155GHz
=9.39nm
5.2GHz
FWHM
1100
1120
1140
1160
1180
1200
DETUNING (GHz)

Fig. 8

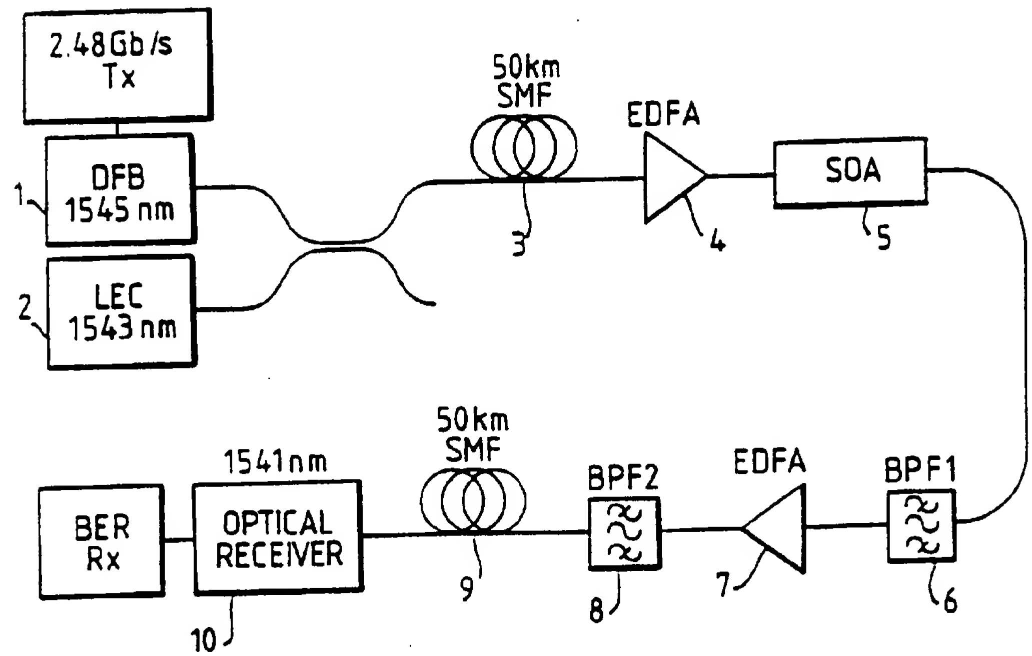

2.48Gb/s
Tx
DFB
1545 nm
LEC
1543 nm
1
2
50km
SMF
3
EDFA
4
SOA
5
BPF1
6
EDFA
7
BPF2
8
50km
SMF
9
1541nm
OPTICAL
RECEIVER
10
BER
Rx

Fig. 9

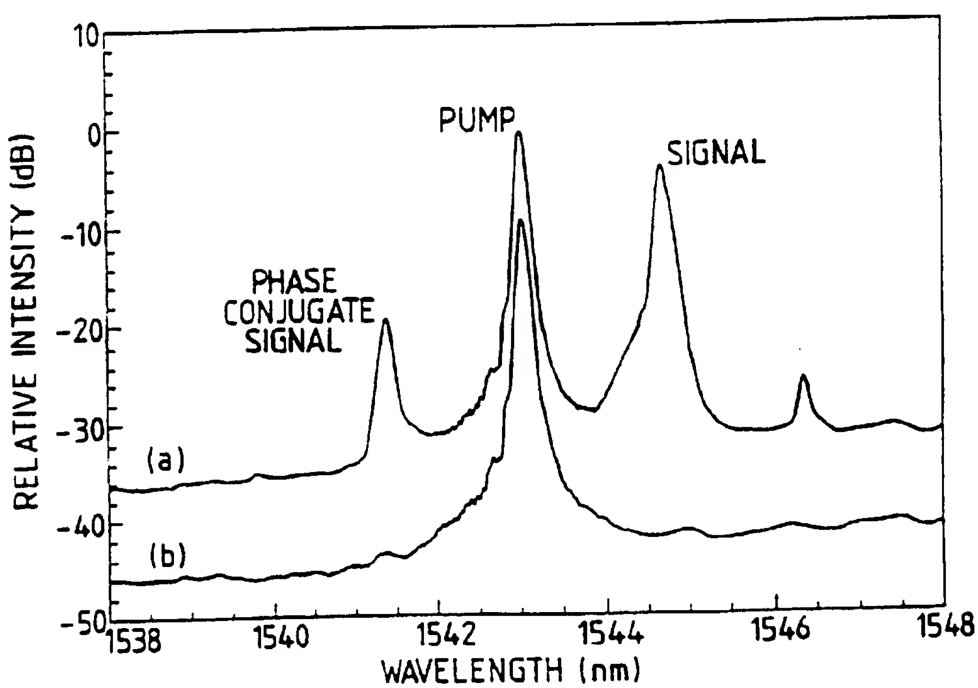

RELATIVE INTENSITY (dB)
10
0
-10
-20
-30
-40
-50
PUMP
SIGNAL
PHASE
CONJUGATE
SIGNAL
(a)
(b)
1538
1540
1542
1544
1546
1548
WAVELENGTH (nm)

Fig. 8a

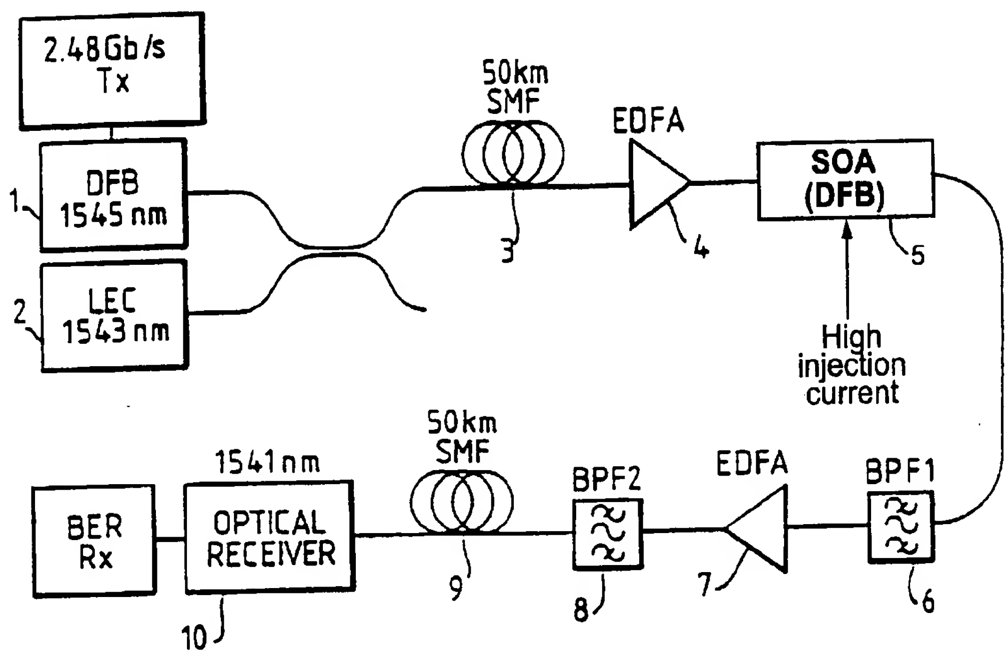

2.48Gb/s
Tx
DFB
1545 nm
1
LEC
1543 nm
2
50km
SMF
3
EDFA
4
SOA
(DFB)
5
High
injection
current
BPF1
6
EDFA
7
BPF2
8
50km
SMF
9
1541nm
OPTICAL
RECEIVER
10
BER
Rx

Fig. 10a

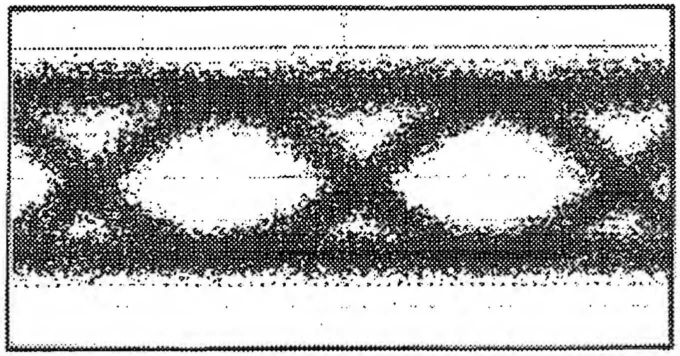


Fig. 10b

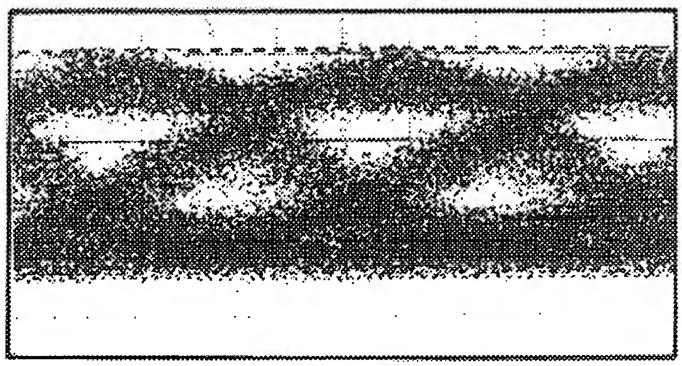


Fig. 10c

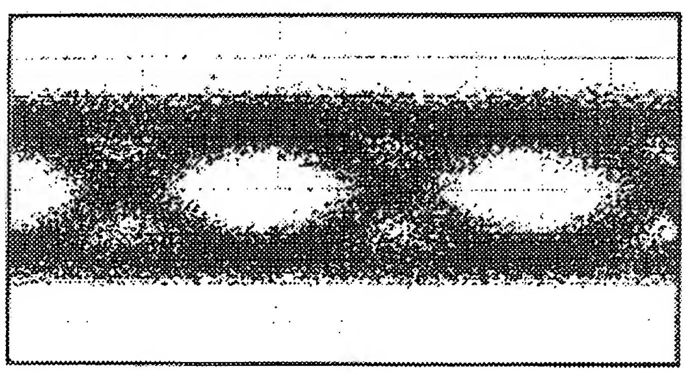


Fig. 11

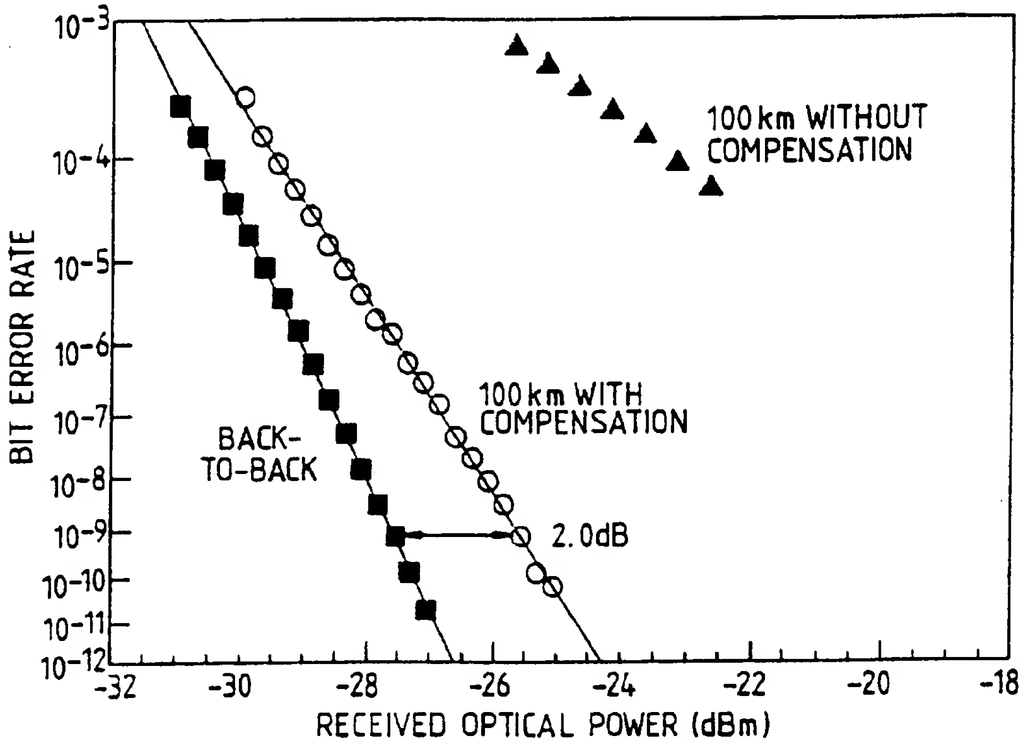

10-3
10-4
10-5
10-6
10-7
10-8
10-9
10-10
10-11
10-12
BIT ERROR RATE
-32
-30
-28
-26
-24
-22
-20
-18
RECEIVED OPTICAL POWER (dBm)
100 km WITHOUT COMPENSATION
100 km WITH COMPENSATION
BACK-TO-BACK
2.0dB

Fig. 12

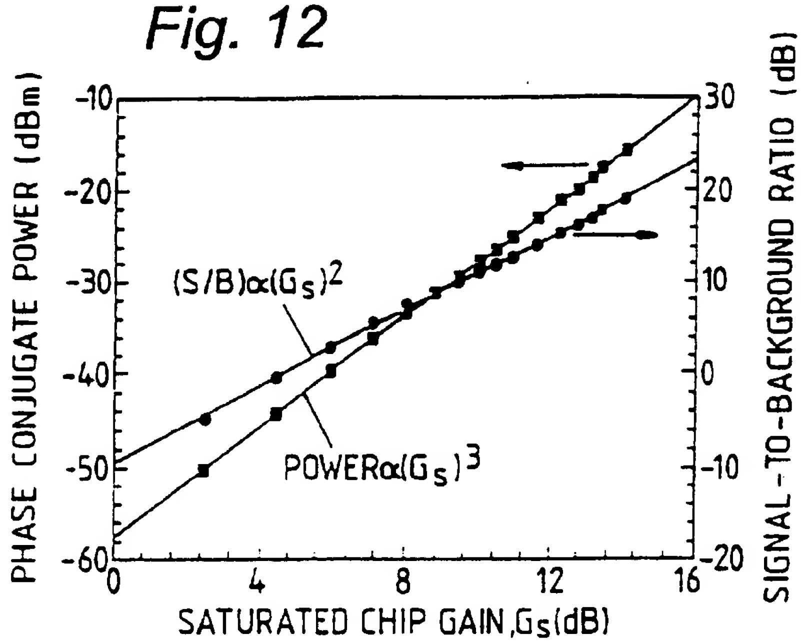
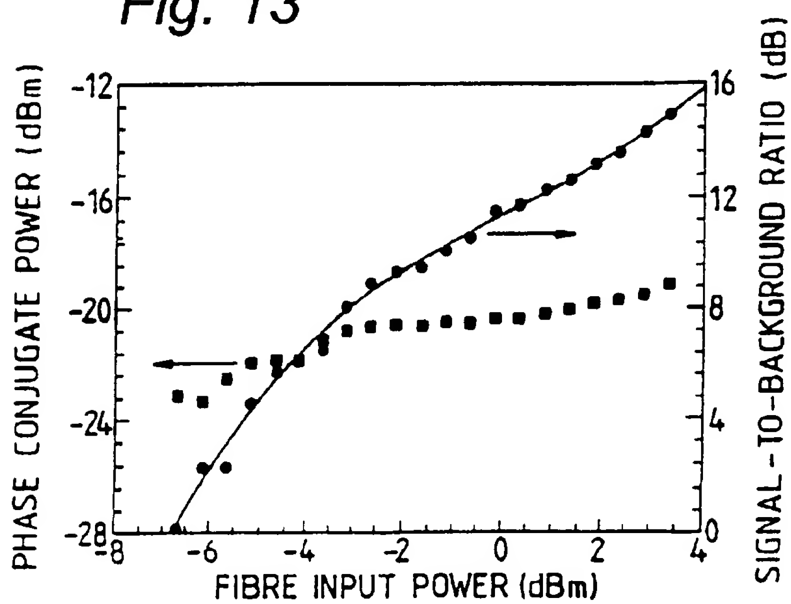

PHASE CONJUGATE POWER (dBm)
-10
-20
-30
-40
-50
-60
0
4
8
12
16
SATURATED CHIP GAIN, Gs(dB)
(S/B)α(Gs)2
POWERα(Gs)3
30
20
10
0
-10
-20
SIGNAL-TO-BACKGROUND RATIO (dB)

Fig. 13


PHASE CONJUGATE POWER (dBm)
-12
-16
-20
-24
-28
-8
-6
-4
-2
0
2
4
FIBRE INPUT POWER (dBm)
16
12
8
4
0
SIGNAL-TO-BACKGROUND RATIO (dB)

# DISPERSION COMPENSATION IN AN OPTICAL COMMUNICATIONS SYSTEM

## BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to methods and apparatus for compensating for dispersion in optical communications systems, and in particular to methods and apparatus employing optical phase conjugation.

2. Related Art

In order to have a high transmission capacity, an optical communications system must have low dispersion, this means that pulses of light travelling along the waveguide, generally an optical fibre, of the optical communications system should not suffer significant distortion. This distortion may arise from a number of sources. If the optical communications system employs multi-mode fibre, each of the different modes will have a different group velocity, thus modulated signals, i.e. pulses of light passing down the multi-mode optical fibre, which are made up of a number of different modes of the waveguide will experience a different group delay from each of their modes. This causes a pulse formed from more than one mode to spread out as it propagates, and is called intermodal dispersion. Once consecutive pulses have spread out so that they are no longer distinguishable, one from the other, the information transmission limit of the optical communications system has been reached. This limit is expressed as a bandwidth distance product since it will be reached at a higher bit rate for a shorter optical communications link. Intermodal dispersion between the modes of multi-mode fibres is one of the reasons why modern optical communications systems have moved to the use of single mode optical fibre which, since it only supports one optical mode, does not suffer from intermodal dispersion.

However single mode optical communications systems do suffer from pulse spreading due to the small, but finite bandwidth of the optical source employed. This type of pulse spreading is called chromatic dispersion, and is due to two effects. Firstly, material dispersion is present because the refractive index of a dispersive medium, such as silica from which optical fibres are typically made, depends on wavelength. Secondly, waveguide dispersion, since the propagation characteristics of the single mode supported by a single mode fibre also depend on wavelength. Since the material dispersion of silica is positive at most wavelengths of interest for optical communications systems, and the waveguide dispersion for single mode fibres is negative, these two effects can be carefully balanced in a well designed optical fibre so as to Vive zero total, chromatic dispersion at the operating wavelength of the optical communications system.

The vast majority of optical communications systems which have been installed worldwide contain single mode optical fibre which has been designed for use in the 1.3 $\mu$m low loss window, and as such has low chromatic dispersion at this wavelength. In recent years the rapid development of erbium doped fibre amplifiers (EDFA) has meant that fibre loss, and thus the power budget of optical communications systems, is no longer the fundamental limit to achievable transmission distance. However these EDFAs are only operable in the 1.55 $\mu$m optical transmission window so that if existing optical communication links are to be upgraded, for example to operate at higher bit rates, these systems must operate in the 1.55 $\mu$m window, over optical fibre designed for use at 1.3 $\mu$m. Thus the fundamental bandwidth distance product transmission limit when upgrading an existing optical communications system is that imposed by dispersion. Furthermore, even for systems having fibre designed for use at 1.55 $\mu$m, as very high bit rates are approached, unless very narrow linewidth, externally modulated lasers are employed, dispersion again is the fundamental limit to transmission capacity.

A number of methods of compensating for dispersion are known. In one such technique the optical signal, at the transmitter end of the optical communications system, is deliberately distorted before being launched into the optical fibre. The distortion imposed upon the optical signal must be calculated so as to be compensated by the dispersion that the optical signal subsequently suffers during propagation along the optimal fibre. An example of such a technique is that disclose& by Koch and Alferness in "Dispersion Compensation By Active Predistorted Signals Synthesis" Journal of Lightwave Technology, volume LT-3, no. 4, August 1985. In order to successfully apply these techniques the transmission characteristics of the particular optical fibre employed, and the length of the transmission link need to be known so that the predistorted signal can be correctly synthenised. Generally the optical source employed in these systems needs to be sophisticated, and thus complex, so at to allow independent control of the amplitude and frequency of the optical signal. The problems inherent in predistortion dispersion compensation systems are considerably exacerbated for higher bit rate systems, where indeed dispersion compensation is of greatest importance.

In a second, known dispersion compensation technique a negative dispersion optical fibre is employed to compensate either at the transmission end, or at the receiver end of the optical link for the positive dispersion suffered by optical signals propagating along the transmission optical fibre. When optical signals at 1.55 $\mu$m are transmitted along a transmission optical fibre having a dispersion zero at 1.31 $\mu$m, the signals will suffer positive dispersion i.e. the sign of the differential of their group delay with wavelength, will be positive, and will typically be of the order of 17 ps/km/nm. Single mode optical fibre can be specifically designed to have a large negative chromatic dispersion, by choosing the waveguide parameters to give large negative waveguide dispersion, for example a fibre having a core of small diameter and high refractive index will have negative waveguide dispersion. Such a scheme was employed by Izadpanah et al in "Dispersion Compensation In 1310 nm Optimised SMFs Using Optical Equaliser Fibre, EDFAs And 1310/1550 nm WDM" Electronics Letters, 16 Jul. 1992, volume 28, no. 15, page 1469. Izadpanah et al employed a specially designed negative dispersion fibre having a dispersion of −45 ps/km/nm. The length of negative dispersion fibre required was approximately one third of the length of the transmission link over which dispersion was being compensated. Such large lengths of additional fibre are clearly inconvenient and expensive. Furthermore due to the high level of doping used in the core, and the small core size this fibre had a relatively high loss, so that amplification of the optical signal is essential, even if the bit rate of the system is not increased.

A third form of dispersion compensation has been theoretically proposed by Yariv et al in "Compensation For Channel Dispersion By Non-linear Optical Phase Conjugation" Optics Letters, volume 4, no. 2, February 1979. Yariv et al proposed that by generating an optical phase conjugate replica of the optical signal after it has passed through one half of the optical transmission link, and launching this phase conjugate replica into the second half of the optical

transmission link, the effects of the dispersion suffered by the optical signal in the first half of the link will be reversed and the optical signal will be restored to its original shape. This technique relies on the time inversion of the group velocity dispersion of the optical signal caused by phase conjugation, and thus requires that the dispersion in the second half of the optical transmission link is the same as the dispersion in the first half, it it is to be fully compensated for.

Yariv's proposal has been implemented in an optical communications system by employing non-degenerate four wave mixing (NDFWM) in dispersion shifted fibre (DSF) to provide the necessary optical phase conjugation. In this case the phase conjugate optical signals travel in the same direction as the copropagating pump light and original optical signal. This technique has been demonstrated by Watanabe et al in "Compensation Of Chromatic Dispersion In A Single Mode Fibre BY Optical Phase Conjugation" IEEE Photonics Technology Letters, volume 5, no. 1, January 1993 and by Jopson et al in "Compensation Of Fibre Chromatic Dispersion By Spectral Inversion" Electronics Letters, 1 Apr. 1993, volume 29, no. 7. In both cases long lengths, over 20 km, of carefully designed DSF were required. A DSF is a fibre which has been designed to have zero dispersion in the 1.55 $\mu$m telecommunications window, i.e. its dispersion zero has been shifted from 1.3 $\mu$m to around 1.55 $\mu$m. In addition to this requirement, Watanabe and Jopson furthermore needed to arrange for the wavelength of the pump light required for NDFWM in the DSF to be the same as the zero dispersion wavelength of the DSF, in order to achieve sufficient phase matching between the pump and the optical signals. This requirement for phase matching over the 20 km of the DSF is severe, and means that the wavelength of the pump light must be carefully controlled e.g. over 20 km with a pump and signal separation of 2 nm the pump wavelength must be within approximately 1 nm of the dispersion zero wavelength. Furthermore this requirement becomes more severe as the length of the DSF increases, and rapidly more severe as the wavelength separation of the pump and signal is increased. The efficiency of conversion of the optical signal to its phase conjugate replica achieved by both Watanabe and Jopson is low, approximately -25 dB in both cases. Thus the phase conjugate signal to be launched into the second half of the optical transmission link is at a very low level.

It has been suggested by Murata et al in "THz Optical Frequency Conversion Of 1 Gb/s Signals Using Highly Non-degenerate Four Wave Mixing In An InGaAsP Semiconductor Laser" IEEE Transactions Photonics Technology Letters, volume 3, no. 11, November 1991, that Yariv's phase conjugation technique for dispersion compensation could be implemented by employing a semiconductor Fabry-Perot laser as the phase conjugating device. This suggestion has not, however been demonstrated.

Another known technique for dispersion compensation is described in "Chirping Compensation Using a Two-Section Semiconductor Laser Amplifier"—Journal of Lightwave Technology, vol. 10, no. 9, September 1992, pages 1247–1254.

## SUMMARY OF THE INVENTION

The present invention provides a method of compensating for dispersion in an optical communications system, the method comprising the steps of

i) positioning a semiconductor optical amplifier between a first and a second length of optical fibre,

ii) launching optical signals into the first length of optical fibre,

iii) directing optical signals emerging from the first length of optical fibre into the semiconductor optical amplifier,

iv) supplying optical pump radiation to the semiconductor optical amplifier so that the optical signals and the pump radiation within the semiconductor optical amplifier generate the phase conjugate of the optical signals, and

v) launching the phase conjugate optical signals into the second length of optical fibre.

The method of the present invention thus overcomes the disadvantages inherent in using DSF to provide optical phase conjugation, by employing a semiconductor optical amplifier. These devices are of a short length, of order one hundred microns, so that phase matching between the pump radiation and the optical signal is easily achieved. Since semiconductor optical amplifiers have gain, the efficiency of the optical phase conjugation process is far higher than for passive DSFs.

The applicants have surprisingly found the method of the present invention successful in compensation for dispersion in optical communications systems, despite the fact that there is substantially no cavity enhancement of the optical phase conjugation in a semiconductor optical amplifier. The theoretical suggestion by Murata et al leads the skilled man to expect that substantial cavity enhancement of the four wave mixing process by a resonant structure, for example a Fabry-Perot laser, is essential to the achievement of sufficient optical phase conjugation efficiency. The applicants have discovered, not only that this is not the case, but that there are significant advantages in employing a semiconductor optical amplifier rather than a semiconductor laser. When a significant degree of cavity, or resonance, enhancement is employed the pump and optical signal must both be accurately controlled in wavelength so that they are coincident with one of the cavity modes, thus requiring accurate wavelength control over these signals. The pump radiation wavelength in particular must coincide with that of one of the cavity modes of the Fabry-Perot laser to injection lock it, and these modes typically have an injection locking bandwidth of only a few GHz. Furthermore the use of resonance enhancement inherently places a limitation on the modulation bandwidth that can be imposed on the optical signal. This is because if the bandwidth of the optical signal begins to approach the bandwidth of the cavity resonance, the cavity resonance will act as a spectral filter to the optical signal, causing distortion of the modulation pattern of the optical signal. This effect will become more severe as the modulation bandwidth of the optical signal increases, and particularly far more severe if the optical signals are not transform-limited, for example if the transmitter has significant linewidth or suffers from chirp. A further disadvantage, inherent to all resonant devices, is their instability under temperature variations or mechanical vibration.

Preferably a semiconductor optical amplifier employed in the method of the present invention has a variation in gain with wavelength, caused by facet reflections, of less than 5 dB i.e. the amplitude of the so called "gain ripple" is less than 5 dB. The Applicants have determined that semiconductor optical amplifiers having a gain ripple less than 5 dBs will not suffer substantially from the disadvantages of cavity enhancement, for example the optical signal bandwidth restriction discussed above. As will be described hereinafter such semiconductor optical amplifiers do, however, benefit to a small degree from some cavity enhancement.

Preferably the semiconductor optical amplifier employed in the present invention has facet reflectivities of less than $10^{-3}$. This effectively ensures that, for single pass gains of up

to 20 dB, the semiconductor optical amplifier is a travelling wave amplifier, having no cavity enhancement.

Preferably the wavelength of the optical signal and the wavelength of the pump radiation are separated by at least 1 nm. This ensures that the four wave mixing undergone by the optical signals and the pump radiation is highly non-degenerate. This is desirable since highly non-degenerate FWM (NDFWM) is based on an ultra-fast intraband optical non-linear gain process which has a very short response time, less than 1 ps, and thus allows the present wavelength dispersion compensation technique to be applicable to optical communications systems operating at bit rates up to tera bits per second.

Advantageously the gain of the semiconductor optical amplifier is saturated by the pump radiation. The applicants have surprisingly discovered that operating the semiconductor optical amplifier under saturation increases the ratio of the phase conjugated signal to the background spontaneous emission.

In addition, or alternatively, the semiconductor optical amplifier is advantageously operated with a high injection current. Although both the level of the phase conjugated optical signals, and the background spontaneous emission increase with increasing injection current, it has been found that the rate of increase in the level of the phase conjugated optical signal is greater than that of the background spontaneous emission, so that the signal to background ratio may be increased by increasing the injection current.

Although the optical pump radiation may be supplied to the semiconductor optical amplifier via the first length of optical fibre, advantageously the optical pump radiation is supplied to the semiconductor optical amplifier from an optical pump source co-located with the semiconductor optical amplifier. This arrangement ensures that the optical pump radiation does not suffer, for example from Brillouin scattering in the first optical fibre.

Advantageously, the optical pump radiation supplied to the semiconductor optical amplifier is generated within the semiconductor optical amplifier. This may be achieved, for example, if both the semiconductor optical amplifier and the optical pump source are comprised by a semiconductor device having wavelength selective feedback means, for example a distributed feedback (DFB) laser, or a distributed Bragg reflector laser. In this case the pump radiation for four wave mixing, rather than being supplied to the semiconductor optical amplifier from an optical pump source distinct from the semiconductor optical amplifier, is generated by the interaction of the wavelength selective feedback means with the gain medium of the semiconductor optical amplifier. Thus, in this case, a single semiconductor device, for example a DFB laser, acts as both a source of narrow linewidth pump radiation, and the non-linear medium in which four wave mixing occurs. Hence only the optical signals are injected into the single semiconductor device, and the phase conjugated optical signals are extracted from the semiconductor device. Preferably the wavelength selective feedback means provide strong optical feedback only at the pump wavelength, so as to avoid causing spectral filtering of the optical signals, or the phase conjugate optical signals.

According to a second aspect of the present invention there is provided an optical communications system comprising a transmission path including a first optical fibre and a second optical fibre, an optical signal source fox launching optical signals into the first optical fibre, an optical pump source for generating pump radiation, and a semiconductor optical amplifier having an input from the first optical fibre and an output to the second optical fibre, wherein, in use, the semiconductor optical amplifier receives the pump radiation and the optical signals, after said signals have propagated through the first optical fibre, and generates phase conjugate replicas of the optical signals, which replicas are launched into the second optical fibre.

According to a third aspect of the present invention a semiconductor optical amplifier is used to provide phase conjugation of optical signals in an optical communication link and thereby to substantially compensate for dispersion suffered by the optical signals during propagation along the optical communications link.

## BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the present invention will now be described, by way of example only, with reference to the accompanying figures, in which

FIG. **1**(*a*) shows the output spectrum of a 500 $\mu$m Fabry-Perot laser with the laser free-running, with 64 mA injection current, FIG. **1**(*b*) shows the injection-locked spectrum of the same laser with −6.7 dBm light coupled into the device from an LEC laser operating at 1.557249 $\mu$m;

FIGS. **2**(*a*) and **2**(*b*) show non-degenerate four-wave mixing in an injection locked Fabry-Perot laser around the 5th resonance, (a) shows the spectrum off-resonance, with the probe laser wavelength between two FP modes, (b) shows the spectrum on resonance, with the probe laser wavelength tuned to the peak of the FP resonance;

FIGS. **3**(*a*) and **3**(*b*) show non-degenerate four-wave mixing in an injection locked Fabry-Perot laser around the 14th resonance, (a) shows the spectrum off-resonance, (b) shows the spectrum on resonance;

FIGS. **4**(*a*) and **4**(*b*) show resonance profiles for (a) the NDFWM conjugate signal, and (b) the probe laser signal, in an injection-locked Fabry-Perot laser;

FIG. **5** shows facet output powers, from a FP laser, of the pump, probe and NDFWM conjugate signals (to short and long wavelengths) at the peak of each resonance, as a function of the pump probe detuning;

FIGS. **6**(*a*) and **6**(*b*) show resonance lineshapes for a FP laser for the pump, probe and NDFWM conjugate signal (short wavelength) for (a) the 5th and (b) the 14th resonance away from the FP resonance at which the pump is injected, the abscissae showing the pump-probe detuning frequencies;

FIG. **7** shows the theoretical variation of the resonance enhancement and the bandwidth of cavity-enhanced NDFWM with gain ripple;

FIGS. **8**–**8***a* show the experimental arrangement for an embodiment of the invention;

FIG. **8**(*a*) shows an alternate embodiment of the FIG. **8** arrangement;

FIG. **9** shows optical spectra measured at the output of the SOA shown in FIG. **8**, (a) with the DFB signal, and (b) without the DFB signal (offset by −10 dB);

FIGS. **10**(*a*)–**10**(*c*) show eye diagrams for the arrangement of FIG. **8** for (a) the back-to-back arrangement, (b) 100 km transmission without dispersion compensation, and (c) 100 km transmission with dispersion compensation (measurements were made using a 2.5 Gbit/s optical receiver, with −26 dBm received power);

FIG. **11** shows bit error rate curves for the back-to-back arrangement, 100 km transmission without dispersion compensation, and 100 km transmission with dispersion compensation 2.488 Gbit/s ($2^{15}-1$) NRZ pseudo-random sequence;

FIG. 12 shows the power of the phase conjugate signal and signal-to-background ratio as a function of the chip gain of a travelling wave amplifier (TWA); and

FIG. 13 shows phase conjugate power and signal-to-background ratio as a function of the total fibre input power (pump+signal). (The curve is a guide to the eye).

## DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENTS

The applicants have carried out experiments, and a theoretical analysis, to determine the effect of cavity enhancement on NDFWM. These experiments and analysis will first be described, followed by a description of an optical communications system according to an embodiment of the present invention.

A number of experiments have been carried out with Fabry-Perot lasers i.e. devices having very high levels of cavity enhancement, by injecting two signals, a pump and a probe into these lasers, and tuning the wavelength of the pump and the probe across the Fabry-Perot (FP) resonances of the lasers. FIG. 1*a* shows the output spectrum from a 500 $\mu$m Fabry-Perot laser, having 16 multiple quantum wells (MQW), when the laser is free running, with 64 mA injection current. It can be seen from this figure that the output on resonance is some 30 dBs greater than off resonances. FIG. 1*b* shows the output spectrum from the same Fabry-Perot laser following injection locking with −6.7 dBm light from the tunable pump source.

Light from the probe source was coupled into the Fabry-Perot laser, maintaining the input power constant at −13.6 dBm (coupled-in power). With the wavelength of the pump maintained at 1.557249 $\mu$m, the wavelength of the probe was tuned through the FP resonances of the pump to longer wavelengths, with up to 9.7 nm (1.19 Thz) detuning between the two inputs. Output spectra with two inputs are shown in FIGS. 2(*a*) & 2(*b*) (for ~3 nm, 370 GHz detuning between the pump and probe and in FIGS. 3(*a*) & 3(*b*) (for ~9 nm, 1.1 THz detuning); in both cases FIG. (a) shows the spectrum off resonance and (b) the spectrum on resonance. The effect of the cavity FP resonances on the NDFWM is, qualitatively, very clear: when the wavelength of the probe lies in between two FP resonances (off resonance), no conjugate signals could be observed, but tuning the probe to the peak of the FP resonance causes a dramatic increase in the conjugate beam power.

The optical power in the NDFWM conjugate beam (to shorter wavelengths) and the probe laser outputs are shown in FIGS. 4(*a*) & 4(*b*), respectively, as a function of the pump-probe detuning. The powers were determined from the measured spectra, but the system was calibrated to obtain actual facet powers. Both the conjugate and probe beams show resonances, corresponding to each of the 14 FP resonances, with narrow linewidth. Though the peak-to-trough ratios for the probe beam resonances are approximately equal to those of the residual FP modes of the FP laser spectrum, the magnitude of the conjugate beam resonances correspond to the square of these amplitudes.

The optical powers of the pump, probe and NDFWM conjugate beams (to both longer and shorter wavelengths) at the peak of the resonances is shown in FIG. 5. The most important feature of the figure is the roll-off of the power of the short wavelength conjugate beam. For detunings of up to 0.9 THz (7.2 nm) the conjugate beam strength decreases at the rate of approximately 10 dB/decade. Above 0.9 THz (7.2 nm) the conjugate beam strength decreases at the rate of approximately 100 db/decade. Above 0.9 THz there is a much more rapid drop in optical power. The absolute power level of the conjugate beam is at least an order of magnitude higher than measured in similar experiments on travelling wave amplifiers for similar input powers. In fact, for detunings up to −0.6 THz (4.8 nm) the power of the conjugate beam at the output facet is higher than the injected power in the probe beam.

The solid line shows the theoretically predicted NDFWM gain (arbitrary scale) given by:

$$gFWM(\omega)\alpha\left|\frac{P_{sat}/(P+P_{sat}}{1-i\omega\tau R}+\frac{\epsilon NL}{1-i\omega\tau_{in}}\right|^2 \tag{1}$$

where $P_{sat}$ is the gain saturation power of the amplifier and P is the total optical power, $\epsilon NL$ is the non-linear gain parameter, $\omega$ is the pump-probe detuning, $\tau R$ and $\tau_{in}$ are the characteristic times of the physical processes giving rise to the two terms, that is, carrier density 'population pulsations' and non-linear gain. $\tau R$ is the effective recombination lifeline (including stimulated emission), and $\tau_{in}$ is the intraband relaxation time. The theoretical curve shown gave a good fit to the experimental data for a 16-well strained layer travelling wave amplifier under similar experimental conditions, with parameters, $\tau R$=0.08 ns and $\tau_{in}$=0.5 ps. The curve gives a reasonable fit to the data for detunings up to 0.9 THz, the relatively slow decay (~10 dB/decade) arising from the combination of the fast decay (20 dB/decade) of the NDFWM due to population pulsations ($\omega >> 1/\tau R$), and the almost constant level of NDFWM from non-linear gain ($\omega \leqq 1/\tau R$).

The rapid decay of the conjugate signal for frequencies above 0.9 THz is due to two effects: (1) the broadening of the resonance resulting from reduced modal gain, and (2) the dispersion of the mode index, resulting in a varying FP mode spacing. Since the enhancement in the conjugate beam power results from the coincidence of both the probe and conjugate beams with FP resonances, the latter effect results in the two beams not being at resonance simultaneously. This effect appears to be dominant, since effect (1) would result in a sharp reduction in the probe output power beyond 0.9 THz detuning, which is not observed.

In order to quantify the enhancement in NDFWM efficiency resulting from cavity resonances, the results described in the previous section will be compared with results on travelling wave amplifiers (TWAs) and DFB lasers. For the TWAs, a pump and a probe beam were injected into a device which had been anti-reflection coated on both facets to ≦0.2%; the devices gave high single-peas gain (~20 dB) with <2 dB residual Fabry-Perot ripple. For the DFB, a single probe input was injected into the device, which was operated well above threshold, emitting >10 mW power.

It is necessary, however, to compare the results in a way which removes the dependence on experimental details, e.g. input powers and single-pass gain. Since the power in the conjugate beam is, in general, described by the relation $P_{fWM} \propto P_1^2 P_2$, where $P_1$, $P_2$, $P_{fWM}$ are the optical powers of the pump, probe and FWM conjugate beams, coefficients $\eta_{out}$ and $\eta_{in}$ are defined for the purposes of comparison in the following way:

$$P_{FWM\ out} = \eta_{out}(P_{1'\ out})^2 . P_{2'\ out} \tag{2}$$

$$P_{FWM\ out} = \eta_{in}(P_{1'\ in})^2 . P_{2'\ in} \tag{3}$$

where the subscripts 'out' and 'in' denote whether the power is the output facet power or the coupled-in input power,

$\eta_{in}$ indicates the basic efficiency of a device for phase conjugation, through this will depend on the single-pass gain at which the device is operated. $\eta_{out}$ gives a better indication of the intrinsic efficiency of each type of device, since this removes the dependence on single-pass gain, and therefore will more clearly show the effect of FP cavity resonances. Table 1 shows the values of $\eta_{out}$ and $\eta_{in}$ for 1 THz pump-probe detuning, for five measurements. Devices numbered 1, 2 and 3 are two facet anti-reflection coated amplifiers, device 4 is a DFB lasers and device 5 is a Fabry-Perot laser. (In all the measurements, the weaker probe beam was to longer wavelength of the pump beam).

| | | Coupled Input Powers | | $(\eta_{out}/mW^2)$ | $(\eta_{in}/mW^2)$ |
|---|---|---|---|---|---|
| | Type | P1 (dBm) | P2 (dBm) | (dB) | (dB) |
| 1 | 2FC Amplifier | −4.5 | −9.2 | −62.2 | −14.2 |
| 2 | 2FC Amplifier | −6.1 | −10.1 | −56.6 | −2.6 |
| 3 | 2FC Amplifier | −7.7 | −12.2 | −56.1 | −2.1 |
| 4 | 3-Section DFB | — | | −60.7 | — |
| | | −9.3 | | | |
| 5 | Uncoated, Injection-Locked | −6.7 | | −30.7 | +7.7 |

The most remarkable feature of the table is that, while the values of $\eta_{out}$ for the TWA and DFB measurements are relatively uniform, the value for the FP device at resonance is ~30 dB greater. This indicates that the effect of the FP cavity is to give roughly three orders of magnitude enhancement in the NDFWM efficiency. There is considerably less difference in the values of $\eta_{in}$ owing to the much lower gain in the F-P device, though as expected, there is less uniformity for the TWA and DFB results.

The results shown in FIG. 4 reveal that the resonance enhancement in the NDFWM occurs over a narrow bandwidth, and this imposes a severe limitation on the use of the effect, both with regard to the maximum bit rates and to the ease of use. The output intensities of the pump, probe and conjugate beam (short wavelength) for a small range of detunings around the resonance are shown in FIG. 6 for (a) the 5th resonance and (b) the 14th resonance. The experimental points for the probe and conjugate beams are fitted using the following Airy-like functions:

$$I_{pr}=I_{pr,0}\,\{[1-RG]^2+4\,RG\sin^2(\Delta k.L)\}^{-1} \quad (4)$$

$$I_{FWM}=I_{FMW,0}\,\{[1-RG]^2+4\,RG\sin^2(\Delta k L)\}^{-2} \quad (5)$$

where $RG=\sqrt{(R_1R_2)}.\exp(gL)$ and $R_1,R_2$ are the facet reflectivities, g is the single-pass gain and L is the device length. $\Delta k$ is the wavevector detuning from the FP resonance, and $\Delta k.L=\pi(\Delta f/\Delta f_{FSR})$ where $\Delta f$ is the frequency detuning and $\Delta f_{FSR}$ is the free spectral range of the FP modes. Equations (4) and (5) are obtained assuming equal, uniform modal gain and effective index for probe and conjugate beams, and uniform pump power.

The parameter RG indicates the degree of feedback within the Fabry-Perot cavity, and in particular the magnitude of the gain ripple (i.e. ratio of the maximum to minimum gain over one cavity mode) in the amplifier is given by

$$\text{Gain Ripple}=\frac{(1+RG)^2}{(1-RG)^2}$$

In both figures, the probe and conjugate beam resonance lineshapes were fitted using the same value of RG (the only variable parameter, apart from the peak intensity), and the measured value of 82.4 GHz was used for $\Delta f_{FSR}$. The full-width at half maximum intensity (FWHM) for the probe and conjugate signals was found to be 4.3 GHz and 2.8 GHz respectively for the 5th resonance; the resonance bandwidth for the 14th resonance was substantially broader, with FWHM values of 8.2 GHz and 5.2 GHz for the probe and conjugate signals respectively. For the 14th resonance, there is also significant difference of 4–5 GHz in the resonance peak positions for the probe and conjugate signals, which support the conclusion drawn previously that the modal dispersion degrades the cavity enhancement at detunings of ≧1 THz.

The narrow bandwidth of the resonance enhancement clearly places a considerable restriction on the usefulness of the effect. Equation (5) shows, however, that there is a trade-off between the resonance bandwidth and the magnitude of the enhancement, and FIG. 7 shows the dependence of the peak resonance enhancement and of the resonance FWHM (as a fraction of $\Delta f_{FSR}$) on the gain ripple. The point where gain ripple=0 corresponds to the case of a TWA with gain g. The figure shows that, in order to obtain a substantial enhancement, say>10, the resonance linewidth would need to be less than 0.18 $\Delta f_{FSR}$ (~15 GHx for a 500 $\mu$m device). In the present case, $\Delta f(\mathrm{FWHM})/\Delta f_{FSR}$ lies in the range 0.033–0.06, corresponding to a resonance enhancement of 250–2000, which is consistent with the value of deduced in the previous action.

The experiments described have shown that extremely large enhancements in the efficiency of wavelength translation of NDFWM may be obtained using cavity-enhancement. Under the experimental conditions, an increase of approximately three orders of magnitude was observed in the NDFWM efficiency, for modest pump powers, for pump-probe detunings of up to 0.9 THz (9.2 nm) phase conjugate.

The usefulness of the effect is, however, limited by the following considerations: (1) the bandwidth for injection-locking is small, typically a few GHz, and therefore requires high stability in the pump and mixing devices. In addition, with two optical inputs, there are regimes in which the injection-locking becomes unstable, when the device tries, in effect, to look to two signals simultaneously. (2) The bandwidth for resonance enhancement is also small. In the measurement, this bandwidth was found to be as small as 2.8 GHz (FWHM). There is a trade-off between the resonance bandwidth and the enhancement obtained, and it is predicted that to obtain a factor of 10 increase in the NDFWM efficiency (compared with that for a travelling wave amplifier) one would be restricted to a bandwidth of ~15 GHz. This not only means that the wavelength of the input signal needs to be finely tunable and stable, but that the maximum bit rate for signals which are to be phase conjugated is limited to ~15 Gbit/s.

These problems can be overcome by using a semiconductor optical amplifier (such as a TWA) which has little cavity enhancement. The main difficulties then encountered lie in obtaining sufficient power and signal-to-background ratio in the phase conjugate signal. Since NDFWM is highly non-linear, these two quantities are strongly dependent on the powers of pump and signal beams within the TWA. To determine the optimum working conditions, these two parameters were measured as a function of (a) the gain of the TWA, and (b) the optical input power.

FIG. 12 shows the phase conjugate power (measured at the output facet) and the signal-to-background ratio (measured by optical spectrum analyser with 0.1 nm resolution) as a function of the chip gain, for constant input

power of +4.8 dBm (total fibre power, pump+signal). The phase conjugate power increases as the cube of the gain of the TWA, giving up to −16 dBm at high injection currents. The signal-to-background ration also increases strongly with the gain, but as the square of the gain. At the highest gains, the ratio is close to 20 dB. The signal-to-background increases less rapidly with the gain than the phase conjugate power owing to the linear dependence of the background spontaneous emission on the gain.

The dependence of the phase conjugate power and the signal-to-background ration on the input power is shown in FIG. **13** for constant TWA injection current of 250 mA (the ratio between pump and signal input power being hold constant). Surprisingly, the phase conjugate power level is quite insensitive to the input power. This, however, may be explained by the small change in the output power of the TWA under strong saturation. The input power, however, does have a strong effect on the signal-to-background ratio. This increases sharply with increasing input power, owing to the reduction in background spontaneous emission. This is an important consideration when attempting to minimise the noise introduced in the phase conjugation.

An embodiment of the present invention will now be described in which FWM in a semiconductor optical amplifier (SOA) is employed to compensate for dispersion in an optical communications system. With reference to FIG. **8**, a DFB laser **1** is used as the transmitter, directly modulated with a 2.488 Gbit/s pseudo-random NRZ $2^{15}$-1 pattern. The DFB laser **1** has a wavelength of $\lambda_s$=1544.7 nm. The bias and modulation of the DFP **1** were chosen to give good extinction ratio but, consequently, large chirp. The signal is combined at the transmitter end of the system with CW light from a pump laser **2**, a long external cavity (LEC) laser operating at $\lambda_p$=1543.1 nm. The combined pump and signal is transmitted across 50 km normal-dispersion single-mode fibre **3**, with a dispersion of 17 ps/nm. km at the signal wavelength. After amplification by an Erbium-doped fibre amplifier **4** (EDFA), the light was coupled into an SOA **5**. The SOA is an etched-mesa buried hetrostructure device with an active layer of InGaAsP and both facets anti-reflection coated to less than $10^{-3}$ reflectivity. The SOA is operated at high injection current (300 mA), but the gain is saturated by the injected light with less than 1 dB residual Fabry-Perot ripple. The phase-conjugate signal is generated by NDFWM within the SOA, with a wavelength given by $\lambda_{PC}=(2\lambda p^{-1}-\lambda_S^{-1})^{-1}=1541.4$ nm. An optical bandpass filter **6** (1.3 nm bandwidth) follows the SOA and allows only the phase-conjugate signal to be transmitted. This signal is amplified by a further EDFA **7** and further filtered by filter **8** (0.6 nm filter) then transmitted across a second 50 km length of single-mode fibre **9**. The signal is detected using a PIN-FET optical receiver **10**.

Spectra at the output of the SOA are shown in FIG. **9**, (a) with and (b) without the signal beam. With the signal and pump both present and with polarisations aligned, the phase-conjugate signal at 1541.4 nm is generated, with the inverted spectral profile of the DFB signal beam. The fibre input powers of the pump and signal beams into the SOA are +2.7 dBm and −4.1 dBm respectively. The background to the spectra is from amplified spontaneous emission from both the EDFA and the SOA and causes a reduction in the signal-to-noise ratio. In order to maximise both the signal-to-noise ratio and conversion efficiency the SOA is operated with high gain and moderately high input optical power. Taking into account the coupling loss into and out of the SOA, the conversion efficiency of the phase conjugation (i.e. ratio of the power of the phase conjugate beam at the output facet to signal power coupled into the SOA) is +2.4 dB, with a phase-conjugate of −5.6 dBm at the output facet of the SOA. This conversion efficiency is at least 20 dB greater than using DSF, and can be further increased by using a SOA with higher output power.

The effect of the dispersion compensation is clearly seen by comparison of the eye diagrams of FIG. **10**, where (a), (b) and (c) correspond to the back-to-back measurement, and 100 km transmission without and with dispersion compensation, respectively. The figures are all taken from the receiver output with −26 dBm received optical power. The effects of fibre chromatic dispersion are evident from the distortion of the eye diagram (b), but the clean eye is completely recovered by the dispersion compensation (FIG. (c)).

Bit error rate (BER) measurements were performed for back-to-back transmission, and 100 km transmission with and without dispersion compensation, and the results are shown in FIG. **11**. The back-to-back measurement, with the DFB signal directly into the receiver, shows a sensitivity of −27.5 dBm. The inclusion of a 0.6 nm bandpass filter results in a power penalty of less than 0.1 dB. Transmission of the DFB signal over 100 km without compensation (with a single EDFA at the transmitter) results in a considerable dispersion penalty, and BERs as low as $10^{-9}$ could not be achieved. A similar eye diagram and BER characteristic were obtained using the arrangement of FIG. **8**, but with the filters tuned to transmit the DFB signal. With dispersion compensation, a dramatic improvement in the BER characteristic is seen, with $10^{-9}$ BER at −25.5 dBm. The 2 dB penalty results both from a reduction in extinction ratio and the introduction of signal-spontaneous beat noise, both arising from the introduction of amplifier spontaneous emission.

Thus chromatic dispersion compensation using optical phase conjugation in a semiconductor optical amplifier has removed the dispersion penalty in the transmission of a directly-modulated 2.5 Gbit/s signal at 1.5 $\mu$m over 100 km of normal dispersion fibre. The efficiency of the phase conjugation is high at +2.4 dB, despite the lack of cavity enhancement.

In an alternative embodiment (FIG. **8**(*a*)) the SOA **5** is provided by a DFB laser having a wavelength of 1543 nm, thus allowing the pump laser **2** to be dispensed with. In this embodiment the pump radiation at 1543 nm is generated within the SOA **5**. Again, in order to maximise the efficiency of phase conjugation the SOA (in this case a DFB) is operated to provide maximum output power, i.e. with a high injection current, typically more than 10 times the threshold current. Furthermore the average power of the optical signal injected into the SOA **5** is limited to a level such that the degree of gain modulation caused in the SOA is small, typically less than 1 dB.

We claim:

**1**. A method of compensating for dispersion in an optical communications system, the method comprising the steps of

i) positioning a semiconductor optical amplifier between a first and a second length of optical fibre,

ii) launching optical signals into the first length of optical fibre,

iii) directing optical signals emerging from the first length of optical fibre into the semiconductor optical amplifier,

iv) supplying optical pump radiation to the semiconductor optical amplifier so that the optical signals and the pump radiation interact within the semiconductor optical amplifier and generate the phase conjugate of the optical signals, and

v) launching the phase conjugate optical signals into the second length of optical fibre.

2. A method as claimed in claim 1, wherein the variation in gain ripple of the semiconductor optical amplifier with wavelength is less than 5 dB.

3. A method as claimed in claim 1, wherein the reflectivity of the facets of the semiconductor optical amplifier is less than $10^{-3}$.

4. A method as claimed in claim 1, wherein the wavelength of the optical signals and the wavelength of the pump radiation differ by at least 1 nm.

5. A method as claimed in claim 1, wherein the wavelength of the optical signals and the wavelength of the pump radiation differ by less than 20 nm.

6. A method as claimed in claim 1, wherein the gain of the semiconductor optical amplifier is saturated by the pump radiation.

7. A method as claimed in claim 1, wherein the semiconductor optical amplifier is operated with a high injection current density.

8. A method as claimed in claim 7, wherein the semiconductor optical amplifier is operated with an injection current density of more than 5 kA/cm$^2$.

9. A method as claimed in claim 7, wherein the semiconductor optical amplifier is operated with an injection current density of more than 10 kA/cm$^2$.

10. A method as claimed in claim 1, wherein the optical pump radiation supplied to the semiconductor optical amplifier is generated within the semiconductor optical amplifier.

11. A method as claimed in claim 1, wherein the first and second lengths of optical fibre have similar levels of dispersion at the operating wavelength of the optical communications system.

12. A method as claimed in claim 1, wherein the optical signals and the pump radiation are arranged to be co-propagating within the semiconductor optical amplifier.

13. A method as claimed in claim 1, wherein the optical signals and the generated phase conjugate optical signals are co-propagating.

14. A method as claimed in claim 1, wherein in step iv) the optical pump radiation is supplied to the semiconductor optical amplifier from a pump source which is co-located with the semiconductor optical amplifier.

15. An optical communications system comprising:

a transmission path including a first optical fiber and a second optical fiber, an optical signal source for launching optical signals into the first optical fiber, an optical pump source for generating pump radiation, and a semiconductor optical amplifier having an input from the first optical fiber and an output to the second optical fiber, wherein, the semiconductor optical amplifier receives the pump radiation and the optical signals, after said signals have propagated through the first optical fiber, and generates phase conjugate replicas of the optical signals, which replicas are launched into the second optical fiber.

16. An optical communications system as claimed in claim 15, wherein both the semiconductor optical amplifier and the optical pump source are comprised by a semiconductor device having wavelength selective feedback means.

17. An optical communications system as claimed in claim 16, wherein said semiconductor device Is a distributed feedback laser.

18. An optical communication system as claimed in claim 15, further comprising an optical filter for filtering the remnant optical signals and pump radiation from the output of the semiconductor optical amplifier before it is launched into the second optical fibre.

19. An optical communications system, comprising:

a first length of optical fiber;

a second length of optical fiber;

a semiconductor optical amplifier disposed between said first and second optical fibers and operatively connecting said first optical fiber to said second optical fiber;

an optical pump source providing pump radiation to said semiconductor optical amplifier; and

an optical signal source launching optical signals into said first optical fiber;

wherein said semiconductor optical amplifier receives said optical signals from said first optical fiber and pump radiation from said optical pump source to generate a phase conjugate of the optical signals, said semiconductor optical amplifier further launching said phase conjugate into said second optical fiber.

20. The optical communications system of claim 19, further comprising:

an optical filter for filtering unwanted optical signals and pump radiation from an output of said semiconductor optical amplifier before launching of said phase conjugate into said second optical fiber.

* * * * *

US006356680B1

(12) **United States Patent**
Kirk et al.

(10) **Patent No.: US 6,356,680 B1**
(45) **Date of Patent: Mar. 12, 2002**

(54) **METHOD AND SYSTEM FOR REMOVAL OF LOW ORDER OPTICAL TRANSMISSION MODES TO IMPROVE MODAL BANDWIDTH IN A MULTIMODE OPTICAL FIBER COMPUTER NETWORK**

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(73) Assignee: **Enterasys Networks, Inc.**, Rochester, NH (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/650,622**

(22) Filed: **Aug. 30, 2000**

**Related U.S. Application Data**

(63) Continuation of application No. 09/082,767, filed on May 21, 1998, now Pat. No. 6,154,589.

(51) **Int. Cl.**[7] .................................................. **G02B 6/26**

(52) **U.S. Cl.** ............................ **385/29**; 385/27; 385/28; 385/38; 385/39; 385/123; 385/42

(58) **Field of Search** ............................ 385/15, 27, 28, 385/29, 31, 38, 39, 123, 88, 42

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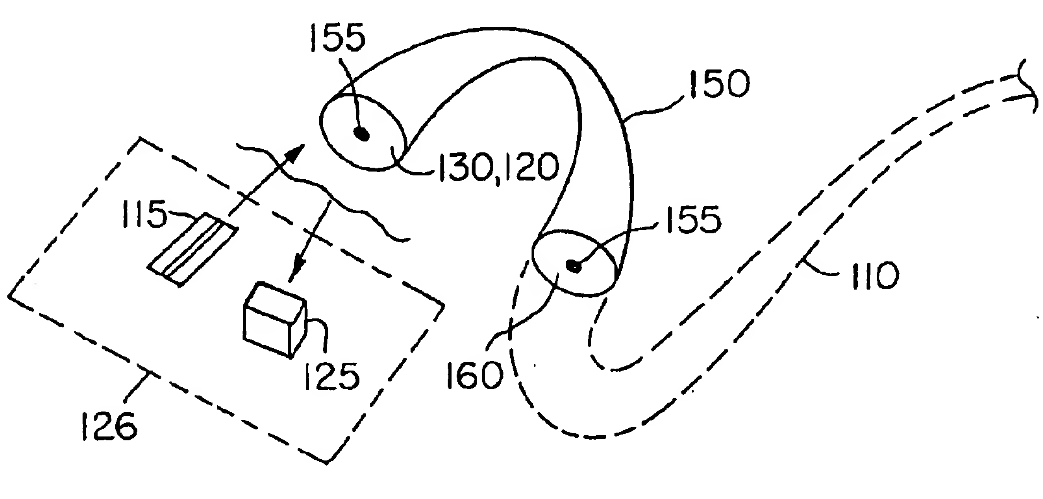
*Primary Examiner*—Brian Healy
(74) *Attorney, Agent, or Firm*—Wolf, Greenfield & Sacks, P.C.

(57) **ABSTRACT**

A method of improving modal bandwidth in computer networks using multimode optical fiber and single mode sources is disclosed in which the optical signal from a center of the optical fiber is prevented from reaching the detector. This is accomplished according to a number of different techniques including the use of opaque spots on the fiber media/fiber couplers or the use of dark-cored fiber couplers. These configurations prevent pulse splitting that occurs in single mode source/multimode fiber systems by preventing light from the multimode fiber's center from interfering with the detector. When this is achieved, the detector is insulated from the effects of pulse splitting, supporting increased data rates by increasing the modal bandwidth.

**18 Claims, 4 Drawing Sheets**



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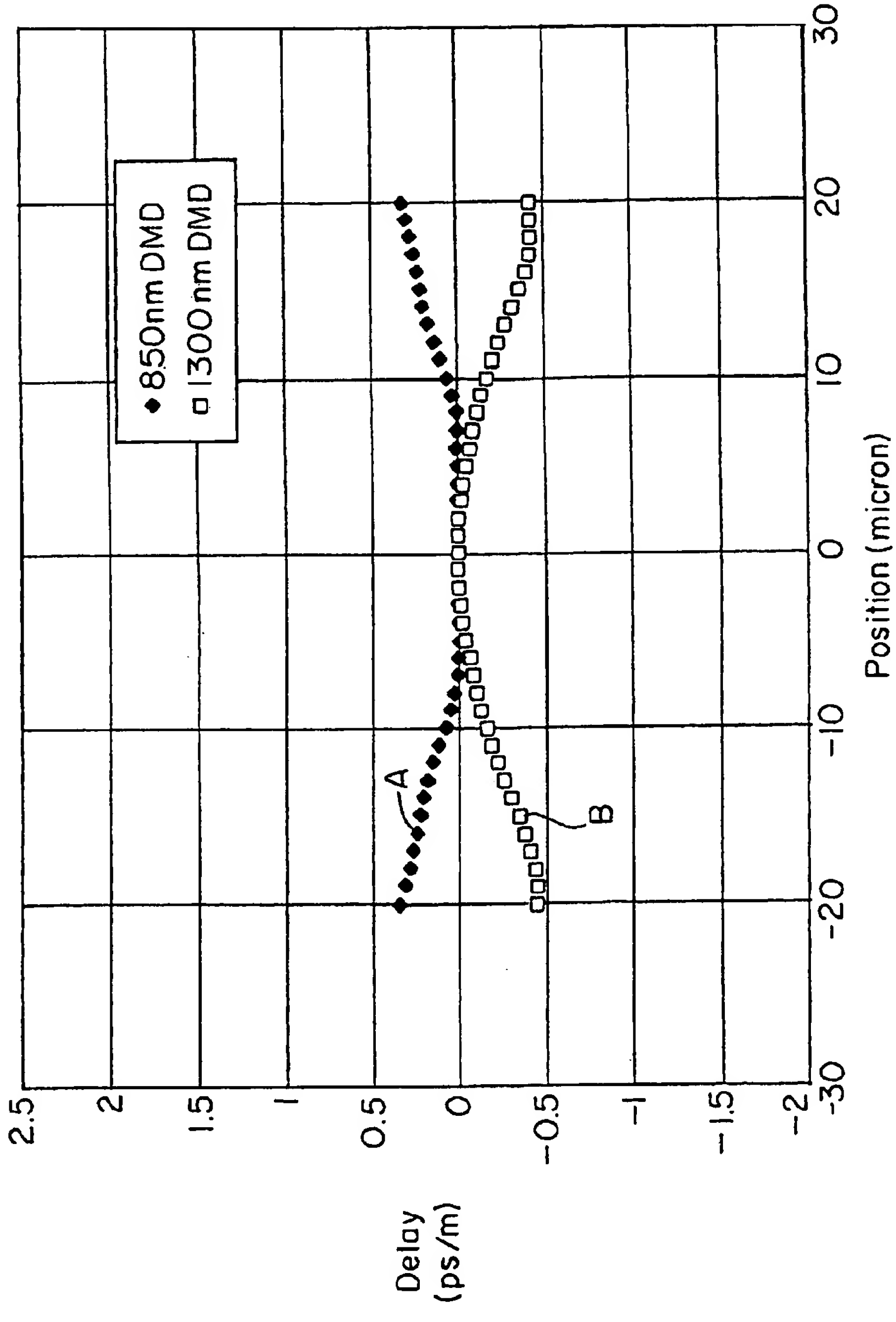
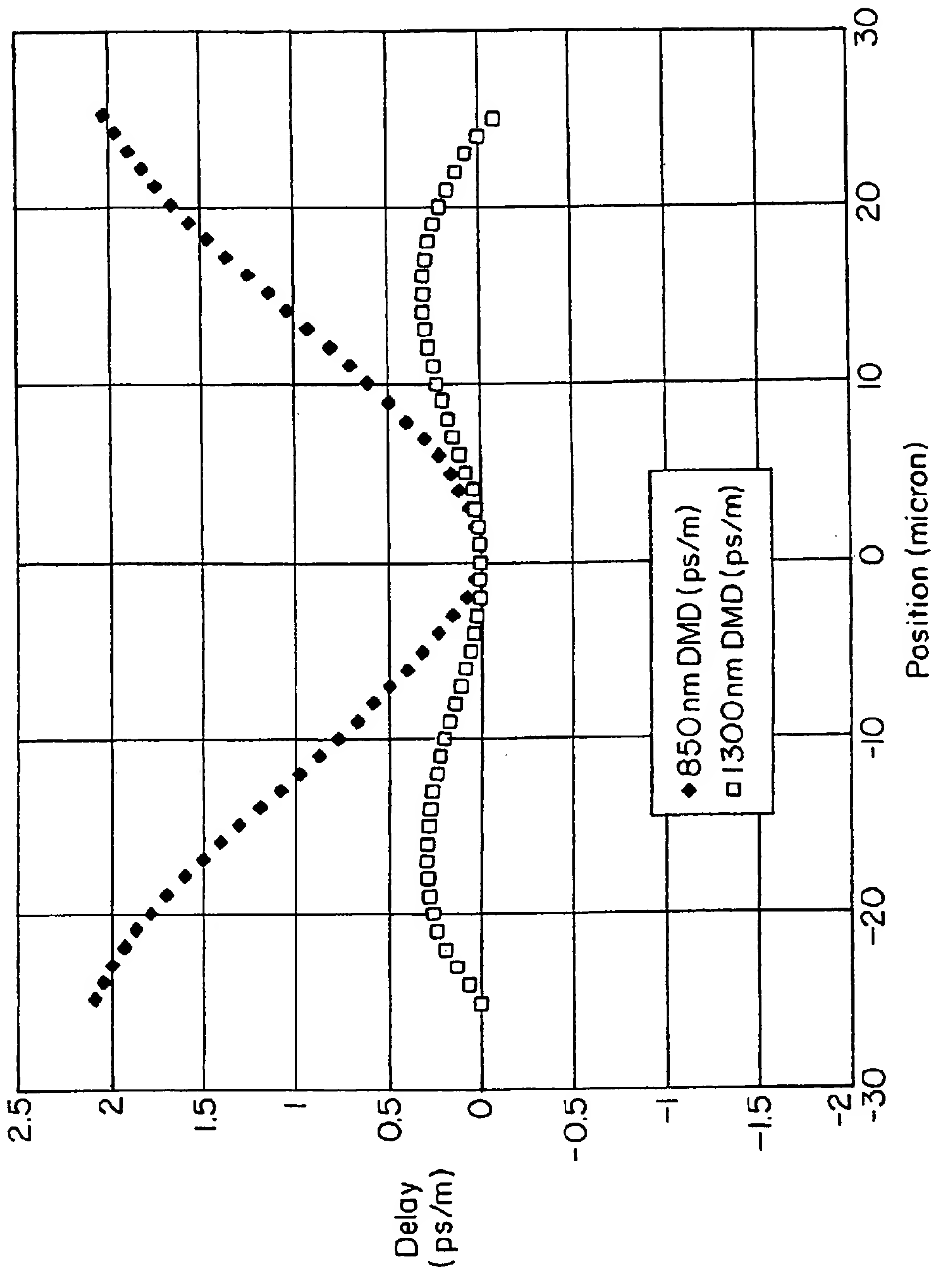

850nm DMD
1300 nm DMD
A
B
Delay (ps/m)
2.5
2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
Position (micron)
−30
−20
−10
0
10
20
30

FIG. 1



Delay (ps/m)
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-30
-20
-10
0
10
20
30
Position (micron)
850nm DMD (ps/m)
1300nm DMD (ps/m)


FIG. 2

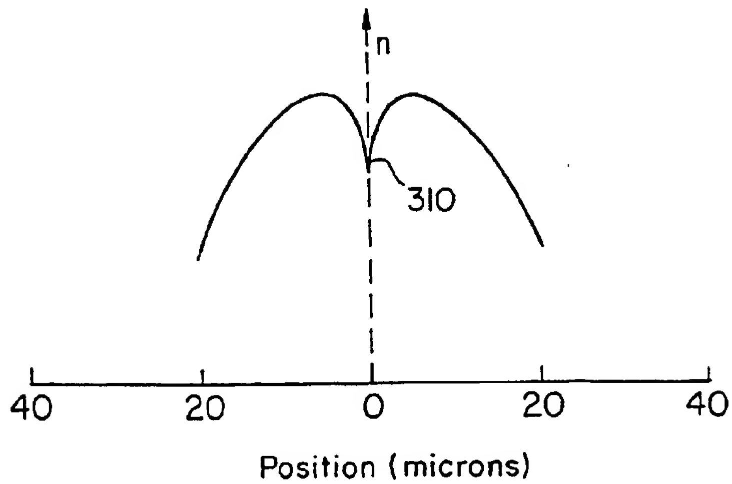

n
310
40
20
0
20
40
Position (microns)

FIG. 3

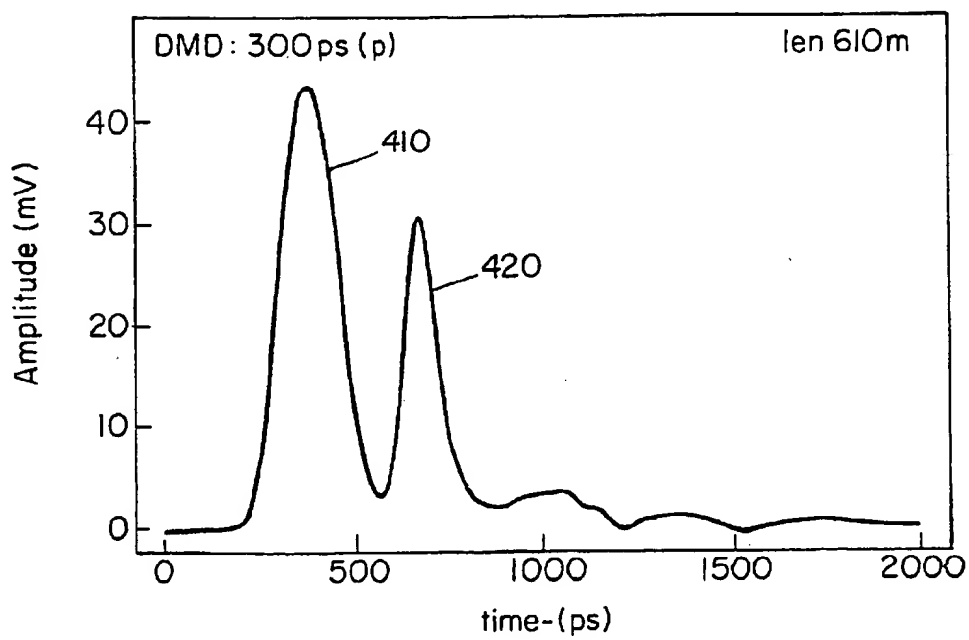

DMD: 300ps (p)
len 610m
40
30
20
10
0
410
420
Amplitude (mV)
0
500
1000
1500
2000
time-(ps)

FIG. 4

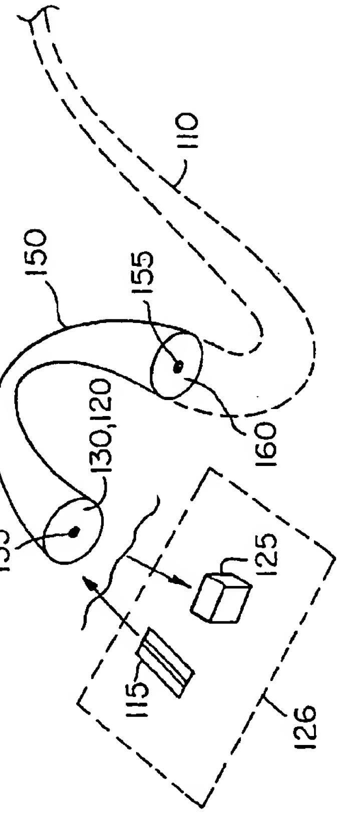


FIG. 6

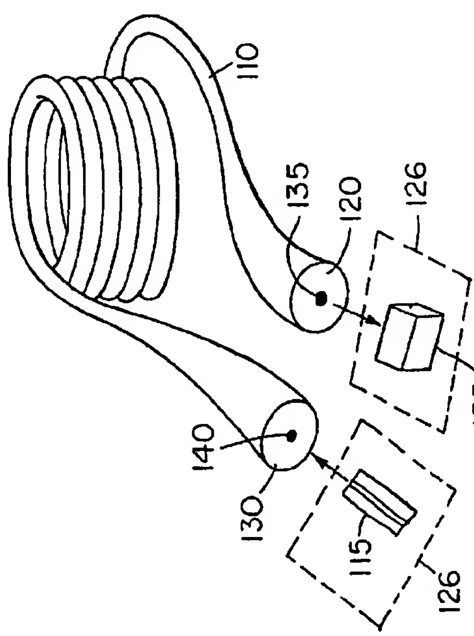


FIG. 5

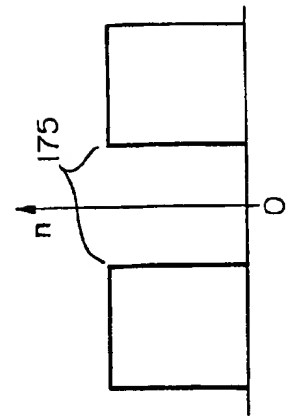


FIG. 8B

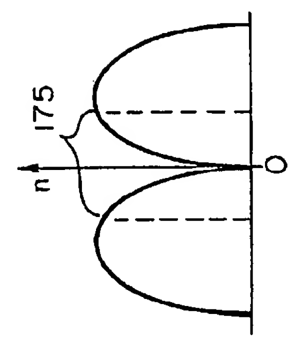


FIG. 8A

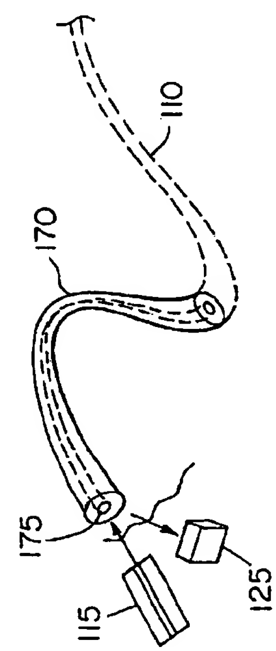


FIG. 7

# METHOD AND SYSTEM FOR REMOVAL OF LOW ORDER OPTICAL TRANSMISSION MODES TO IMPROVE MODAL BANDWIDTH IN A MULTIMODE OPTICAL FIBER COMPUTER NETWORK

This application is a continuation of U.S. patent application Ser. No. 09/082,767 filed on May 21, 1998, and now U.S. Pat. No. 6,154,589.

## BACKGROUND OF THE INVENTION

Historically, local area computer networks (LANs) using optical data links have relied on light emitting diode (LED) sources launching into multimode optical fibers. The EIA/TIA and IEC Building Wiring Standards (TIA 568A) specify the use of 62.5/125 micron multimode optical fiber for intra-building wiring. These standards have resulted in the large-scale deployment of multimode optical fiber in existing computer networks.

In prior communication application technologies, these data transmission platforms have provided adequate bandwidth. Asynchronous transfer mode (ATM) computer networks can support data transmission rates as high as 622 megabits/sec (MBPS), but LED rise times, the chromatic dispersion associated with the relatively wide bandwidth of light produced by the LEDs, and multiple fiber transmission modes impose an upper cap on the potential data rates. Thus, LED/multimode fiber systems are generally limited to sub-gigabit/second (GBPS) data rates.

Newer computer applications requiring higher bandwidths and the increasing number of users that must be serviced by individual networks have led the push to provide GBPS performance, and better. In order to attain this performance in the context of existing optical data links, the LED light sources have been replaced with single mode sources such as vertical cavity surface emitting lasers (VCSEL) and Fabry-Perot lasers. These devices can produce the necessary rise times and have the narrow spectral widths required for GBPS data transmission speeds.

Computer network links modified to use single mode laser sources, however, many times still fail to achieve the data/error rates at GBPS data rates that would be predicted solely from the laser source performance. The problem has been traced to computer links using multimode optical fiber. In many instances, a pulse-splitting phenomena is detected, which increases the bit error rates to unacceptably high levels at these speeds.

The obvious solution to this problem is to use single mode fiber with the single mode sources. While being viable for newly installed computer networks, such a solution is impractical for the installed base of multimode fiber networks since running new fibers in and between buildings represents a significant expense.

Other solutions have been proposed to constrain pulse splitting in signals from single mode sources that have been launched into multimode fibers. In one case, the signal from the single mode source is launched into a short-length pigtail of single mode fiber. The other end of this fiber is then coupled to the existing multimode fiber, offset from the multimode fiber core center.

The problem with the offset single mode-multimode fiber coupling solution is the difficulty of implementing it in the typical computer network environment. The single mode fiber must be precisely misaligned to the multimode fiber such that the light is still launched into the multimode fiber with acceptable efficiency, and this misalignment must be maintained in the coupling module across its lifetime.



## SUMMARY OF THE INVENTION

According to the present invention, pulse splitting is constrained in single mode source/multimode fiber systems by preventing light from the center of the multimode fiber from being transmitted to the detector. When this is achieved, the detector is insulated from the effects of any pulse splitting, supporting data rates of greater than one GBPS by increasing the modal bandwidth.

In general, according to one aspect, the present invention features a method for improving modal bandwidth in an optical link, such as in a computer optical network, using a multimode optical fiber. The method comprises generating an optical signal with a single mode laser source and coupling the optical signal into the multimode optical fiber. The optical signal from a center portion of the optical fiber, however, is blocked from reaching a detector of the optical signal.

In one implementation, the source is a Fabry-Perot or vertical cavity surface emitting laser.

In specific embodiments, an opaque spot is inserted between the laser source and the detector to block the center of the optical fiber from transmitting a detectable optical signal. As such, the spot is applied to a fiber coupler or the fiber of the network. Further, the spot may be applied to either the entrance or exit apertures of the fiber. In any case, the spot should be approximately 4 to 7 microns in diameter.

Alternatively, a fiber coupler with a dark central core is also useful. It can be inserted either at the detector or laser source end of the optical fiber, or both.

According to another aspect, the invention features multimode optical fiber of the computer network with at least one opaque spot for blocking the optical signal from a center portion of the optical fiber from reaching the detector.

Finally, according to another aspect, the invention also features a fiber coupler with a dark core for blocking the optical signal from a center portion of an installed multimode optical fiber from reaching a detector.

The above and other features of the present invention, including various novel details of construction and combinations of parts, and other advantages, will now be more particularly described with reference to the accompanying drawings and pointed out in the claims. It will be understood that the particular method and device embodying the invention are shown by way of illustration and not as a limitation of the invention. The principles and features of this invention may be employed in various and numerous embodiments without departing from the scope of the invention.

## BRIEF DESCRIPTION OF THE DRAWINGS

In the accompanying drawings, like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention.

FIGS. 1 and 2 are plots of the differential mode delay in picoseconds per meter as a function of axial launch position for 850 nanometer and 1300 nanometer sources in two exemplary multimode fiber samples;

FIG. 3 is a plot of the index of refraction (n) as a function of axial position for an exemplary multimode fiber;

FIG. 4 shows a pulse function input signal from a 1300 nm single mode Fabry-Perot laser launched into a 610 meter long, 62.5 micron, fiber run (horizontal scale is 500 ps/division, and the vertical scale is 10 milliVolts/division);

FIG. 5 is a schematic drawing showing embodiments of the inventive system for increasing modal bandwidth by preventing center mode light from reaching the detector;

FIG. 6 is a schematic drawing showing other embodiments of the invention using a fiber coupler;

FIG. 7 is a schematic drawing showing still other embodiments of the invention using a dark core fiber coupler; and

FIGS. 8A and 8B are two refractive index profiles for the dark core fiber.

## DETAILED DESCRIPTION OF THE INVENTION

The modal bandwidth of graded index multimode optical fiber depends directly on the fiber's refractive index profile. The profile is designed to compensate for the different paths traveled by the numerous optical modes supported by the multimode optical fiber. The goal is to equalize delays of all propagating modes. The propagation time of an optical mode through a fiber is proportional to the optical path length. Low order modes propagate nearly straight through the fiber, traveling a distance close to the fiber's physical length L. Higher order modes travel at higher angles, and the physical distance L traveled is consequently longer. The optical path length of all modes is a product of the distance traveled and the refractive index of the optical medium along their respective paths. Compensation for the different modal physical distances is achieved by lowering the refractive index of the region of the fiber in which the higher order modes travel.

The index of refraction compensation is performed during the manufacture of the fiber. When the index is graded correctly, modes of different orders will propagate at compensated velocities and arrive at the far end of the fiber at nearly the same time. Research has shown that the optimum grading is obtained with a refractive index profile of the form:

$$n(r)=n1^{*}[1-2\Delta n[1-(r/a)^{g}]]^{0.5} \text{ for} < a,$$

and

$$n(r)=n2 \text{ for } r>=a,$$

where:

n(r) is the refractive index at radial position r,

n1 is the refractive index peak value,

n2 is the refractive index of the cladding glass,

a is the core diameter,

$\Delta n$ is the index difference$=(n1^2-n2^2)/(2^{*}n1^2)$, and

g is the profile parameter, a value of g=1 gives a straight line curve from 0 to a, a value of g=∞ gives a flat, or step index profile.

A g value of approximately 1.9 to 2.0 has been found to provide optimal propagation delays for multimode optical fibers.

Differential mode delay (DMD) measurements are a method for testing the effectiveness of the index profiling. A fiber is tested by launching a single mode pulse into the core at the core/cladding boundary. The output of the fiber is detected with a high bandwidth detector. The input point is then traversed across a diameter of the fiber while the relative time difference is read and recorded at the other end. The relative delays are plotted against radial position. Fibers with lower DMD profiles, or differences between the delays experienced at the fiber's center relative to near the core/cladding interface, have higher modal bandwidths than those with high DMD profiles.

FIG. 1 is a plot of the DMD for a graded index multimode fiber. Curves A and B show a relatively acceptable DMD for a multimode fiber operating at **850** (see ◇ data points) and **1300** (see □ data points) nanometers (nm), respectively. In each case, the DMD is less than 0.5 picoseconds per meter (ps/m).

FIG. 2 is a plot of the DMD for another multimode, nominally similar, fiber. The DMD is limited for 1300 nm, but at 850 nm the DMD reaches 2 ps/m for modes launched at a fiber axial position of+/-25 microns from the fiber's center. As a result, when operating at 850 nm, modes transmitted along the fiber's center travel much faster than those near the cladding/core interface.

The reduced delay for modes traveling along the fiber's center is theorized to be an artifact of the manufacturing techniques used for the multimode fiber. The fibers are manufactured by slowly depositing closely controlled combinations of chemicals on the inner surface of a hollow glass tube. This process slowly closes the tube off, slowly reducing its inner diameter by the sequential depositions. The last stages, just before the tube is closed-off, can sometimes be incomplete, yielding indexes such as that illustrated in FIG. 3 when the tube is pulled into the fiber. A sharp anomaly **310** in the graded index (n) occurs near the fiber's center, position **0**.

It is theorized that the fiber's center index of refraction anomaly results in pulse splitting such as that shown in FIG. 4 when a single mode laser launches into a multimode fiber. In an experiment, a 1300 nm single mode Fabry-Perot laser launched a pulse function into a 610 meter long, 62.5 micron, fiber run. In the plot, the horizontal scale is 500 ps/division, and the vertical scale is 20 milliVolts/division.

After propagating the 610 meters, the original signal is converted into an initial pulse 410 and a secondary pulse 420. This pulse splitting differs from the pulse broadening usually seen when multimode sources are launched into multimode fibers.

The highly multimodal and wide bandwidth characteristics of the LED are believed to excite all or most of the fiber's transmission modes. As a result, a relatively small amount of the energy carried by the fiber is transmitted in the fiber's center and thus experiences the problematic transmission delay associated with the center index anomalies. In contrast, it is believed that the single mode laser source excites relatively few of the fiber's modes. Some of those modes propagate along the fiber's center, experiencing little delay, and an almost equivalent optical power is contained in other modes that propagate more toward the cladding/core interface, experiencing delay that would be predicted from the graded fiber configuration. These effects result in the distinct splitting, which severely undermines the decision logic in the detector yielding unacceptably high error rates when the transmission speeds approach 1 GBPS. While not all existing multimode fiber has this problem, a non-trivial amount does, and there is no easy test for identifying the problem fibers.

FIG. 5 illustrates one embodiment of a system for preventing the pulse splitting in multimode fiber 110/single mode source 115 computer data network transmission systems. Briefly, the invention is based on the principle that an opaque spot, applied to the center axis of the multimode fiber, between the detector and source, prevents the fiber modes traveling along the fiber's center axis from reaching the detector. Experiments have shown that stopping the coupling of the fiber's center modes to the detector prevents either the pulse splitting effect entirely or the effect at the detector where it causes problems.

In the embodiment of FIG. **5**, an opaque spot **135** is applied to exit aperture **120** of the fiber **110**, which forms the optical transmission media of the network. This configuration prevents any center modes of the optical signal propagating in the multimode fiber **110** from reaching the detector **125**, which is typically part of a network interface card **126** of the computer node or network communications device. As a result, the center modes, which may propagate too quickly due to a reduced center index of refraction present in some multimode fibers, will not contribute to a pulse splitting effect at the detector **125** thereby preserving modal bandwidth.

The opaque spot **135** is preferably large enough to prevent substantially all of the energy in the center modes from reaching the detector **125**. In the preferred embodiment, the opaque spot blocks approximately 90% of the energy. This requires a spot approximately 5 to 7 microns in diameter for 62.5 micron fiber. The opaque spot is preferably circular and applied substantially centered on the fiber's axis, as shown.

The opaque spot **135** is applied according to a number of different techniques. In the preferred embodiment, it is painted-on, possibly using a jig. Alternatively, it is scribed, etched, or deposited on the fiber end.

As also shown in FIG. **5**, an opaque spot **140** is alternatively applied to the input or entrance aperture **130** of the fiber **110**. This second configuration prevents the optical signal from the single mode laser source **115**, typically also found in a network interface card **126**, from exciting any of the center modes of the fiber **110**. A characteristic of multimode fibers that allows this embodiment to work is the limited coupling between the fiber's modes. That is, the center modes will not be excited by optical power crossing over from other modes.

According to the invention, the opaque spot is applied to the fiber's input aperture **130** or output aperture **120**, individually. Alternatively, opaque spots **140, 135** are applied to both of the input and output apertures **130, 120**.

FIG. **6** shows another embodiment in which the opaque spot(s) is/are not necessarily applied to the existing multimode fiber **110** but applied to a fiber pigtail or coupler **150** between the existing multimode fiber **110** and the single mode light source **115** and/or detector **125**. As before, the fiber couplers **150** are used at the detector or laser ends, or both. Moreover, the opaque spots **155** on the coupler **150** can be applied to the entrance/exit aperture ends **130, 120** that face the laser **115**/detector **125** or to the coupler end **160** that interfaces with the multimode fiber **110**, or both.

FIG. **7** shows still another embodiment of the invention. In this case, a coupler **170** is used as in the embodiment in FIG. **6**. The fiber coupler's refractive index, however, is constructed so that it has a dark core **175** that can not transmit light, rather than the reliance on the opaque spots.

FIGS. **8**A and **8**B show two index profiles that will not transmit any light through the fiber's center axis. By doping the fiber during its manufacture such that the index of refraction drops sharply near the fiber's center axis, as shown in FIG. **8**A, light will be coupled only into modes existing in an annular ring centered on the fiber. Similarly, FIG. **8**B shows a fiber index with an annular step profile. Here, the center 5–7 microns of the fiber transmits no light. As in the previous embodiments, these dark core couplers **170** are placed either at the front end between the transmission fiber **110** and the laser **115** at the tail end between the transmission fiber **110** and the detector **125**, or both.

While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. Those skilled in the art will recognize or be able to ascertain using no more than routine experimentation, many equivalents to the specific embodiments of the invention described specifically herein. Such equivalents are intended to be encompassed in the scope of the claims.

What is claimed is:

**1**. A method of improving modal bandwidth of a multimode optical fiber, comprising:

applying a blocking area to the multimode optical fiber such that substantially no optical signal exits from a center portion of the multimode optical fiber, wherein the blocking area comprises an opaque spot.

**2**. A method of improving modal bandwidth of a multimode optical fiber, comprising:

applying a blocking area to the multimode optical fiber such that substantially no optical signal exits from a center portion of the multimode optical fiber; and

generating the optical signal with one of:

a single-mode laser source;

a Fabry-Perot laser; and

a vertical cavity surface emitting laser.

**3**. The method as recited in claim **1**, wherein the blocking area is positioned over a center axis of the multimode optical fiber.

**4**. The method as recited in claim **1**, further comprising applying the blocking area to at least one of the exit aperture and an entrance aperture of the multimode optical fiber.

**5**. A method of improving modal bandwidth of a multimode optical fiber, comprising:

applying a blocking area to at least one of the exit aperture and an entrance aperture of the multimode optical fiber such that substantially no optical signal exits from a center portion of the multimode optical fiber;

wherein the blocking area is applied by at least one of:

painting;

scribing;

etching; and

depositing.

**6**. A method of improving modal bandwidth of a multimode optical fiber, comprising:

applying a blocking area to the multimode optical fiber such that substantially no optical signal exits from a center portion of the multimode optical fiber; wherein the blocking area is a spot having a diameter that is approximately 6.5% to 11.2% of a diameter of the multimode optical fiber.

**7**. A method of improving modal bandwidth of a multimode optical fiber, comprising:

applying a blocking area to the multimode optical fiber such that substantially no optical signal exits from a center portion of the multimode optical fiber; wherein the blocking area is of a construction sufficient to block at least 90% of the energy in the center modes of the multimode optical fiber.

**8**. An optical signal transmission system, comprising:

multimode optical fiber; and

a blocking area comprising an opaque spot applied to the multimode optical fiber such that substantially no optical signal exits from a center portion of the multimode optical fiber.

**9**. The system as recited in claims **8**, wherein the blocking area is positioned over a center axis of the multimode optical fiber.

10. The system as recited in claim 8, wherein the blocking area is applied to at least one of an exit aperture and an entrance aperture of the multimode optical fiber.

11. An optical signal transmission system, comprising:

multimode optical fiber; and

a blocking area applied to the multimode optical fiber such that substantially no optical signal exits from a center portion of the multimode optical fiber, wherein the blocking area is of a construction sufficient to block at least 90% of the energy in the center modes of the multimode optical fiber.

12. An optical signal transmission system, comprising:

multimode optical fiber; and

a blocking area applied to the multimode optical fiber such that substantially no optical signal exits from a center portion of the multimode optical fiber, wherein the opaque spot has a diameter that is approximately 6.4% to 11.2% of a diameter of the multimode optical fiber.

13. An optical signal transmission system, comprising:

multimode optical fiber; and

a blocking area applied to the multimode optical fiber such that substantially no optical signal exits from a center portion of the multimode optical fiber;

wherein the blocking area is applied by at least one of:

painting

scribing

etching; and

depositing.

14. An optical signal transmission system, comprising:

multimode optical fiber; and

a fiber coupler, coupled to the multimode optical fiber, to substantially prevent an optical signal from exiting a center portion of the multimode optical fiber,

wherein the fiber coupler comprises an opaque blocking spot applied to at least one of an exit aperture and an entrance aperture of the fiber coupler.

15. The system as recited in claim 14, wherein the fiber coupler transmits only an annular ring of light into the multimode optical fiber.

16. An optical signal transmission system, comprising:

multimode optical fiber; and

a fiber coupler, coupled to the multimode optical fiber, to substantially prevent an optical signal from exiting a center portion of the multimode optical fiber,

wherein the fiber coupler comprises a blocking area applied to at least one of an exit aperture and an entrance aperture of the fiber coupler, and the blocking area is of a construction sufficient to block at least 90% of the energy in the center modes of the multimode optical fiber.

17. An optical signal transmission system, comprising:

multimode optical fiber; and

a fiber coupler, coupled to the multimode optical fiber, to substantially prevent an optical signal from exiting a center portion of the multimode optical fiber,

wherein the fiber coupler comprises a blocking area applied to at least one of an exit aperture and an entrance aperture of the fiber coupler, and the fiber coupler further comprises optical fiber having a first end being the entrance aperture of the fiber coupler and a second end being the exit aperture of the fiber coupler, wherein the blocking area is applied to at least one of the entrance aperture and the exit apertures of the optical fiber of the fiber coupler.

18. The system as recited in claim 17, wherein the blocking area is applied by at least one of:

painting;

scribing;

etching; and

depositing.

* * * * *

US006359716B1

(12) **United States Patent**
**Taylor**

(10) **Patent No.: US 6,359,716 B1**
(45) **Date of Patent: Mar. 19, 2002**

(54) **ALL-OPTICAL ANALOG FM OPTICAL RECEIVER**

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(73) Assignee: **Massachusetts Institute of Technology**, Cambridge, MA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/256,954**

(22) Filed: **Feb. 24, 1999**

(51) **Int. Cl.**[7] .............................................. **H04B 10/06**
(52) **U.S. Cl.** ........................ **359/189**; 359/193; 359/195
(58) **Field of Search** ................................ 359/189, 193, 359/195

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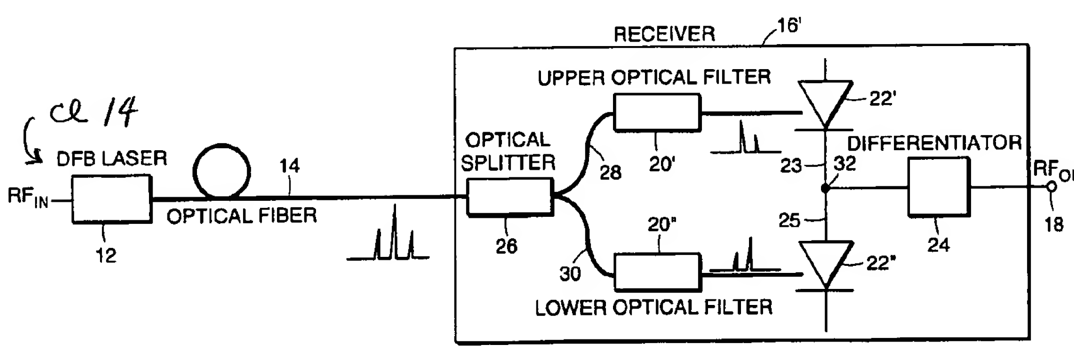
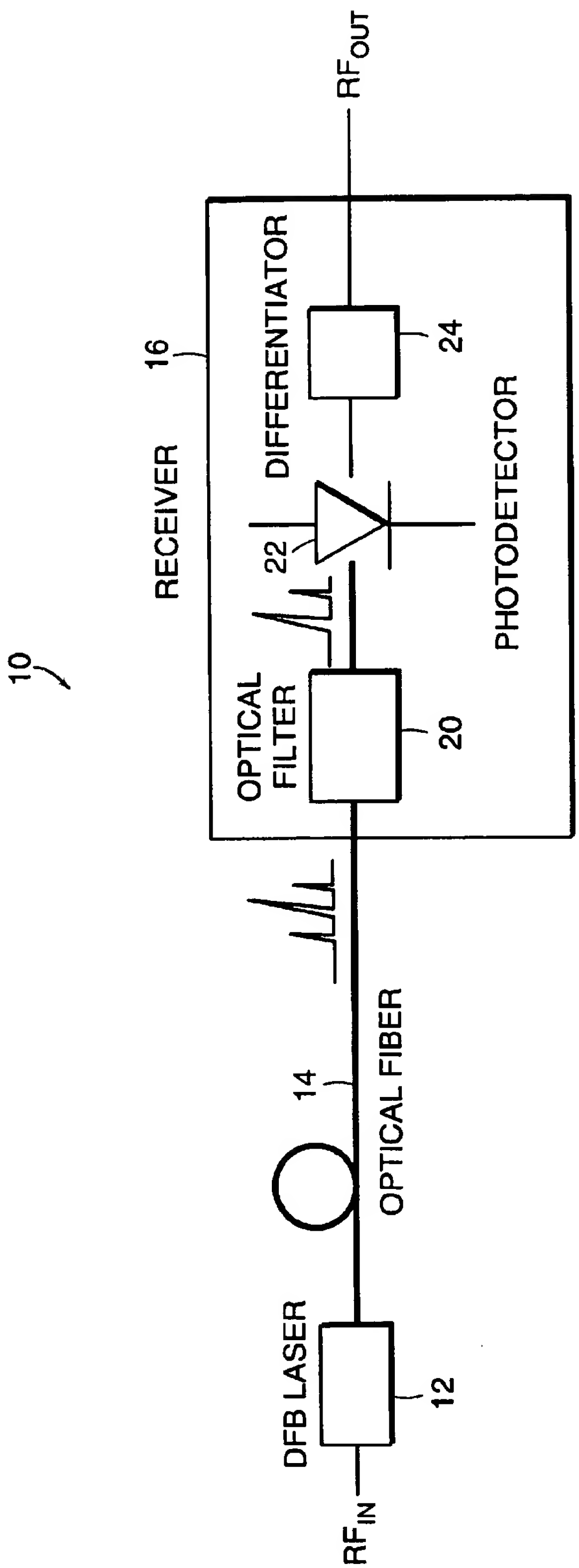
*Assistant Examiner*—Hanh Phan
(74) *Attorney, Agent, or Firm*—Testa, Hurwitz & Thibeault, LLP

(57) **ABSTRACT**

Method and apparatus for an analog FM optical link having a low noise figure and a high spurious-free dynamic range. In one embodiment, the apparatus includes a FM DFB laser and a balanced receiver. The balanced receiver includes an optical splitter to split the received beam into two optical paths. Each of the two paths includes an optical filter and a photodetector. A differentiator coupled to the electrical output of the photodetectors produces a demodulated electrical signal in response to the RF signal used to modulate the DFB laser. This configuration can eliminate the laser relative intensity noise and second order harmonics. In addition, third order distortion is eliminated when there is no intensity modulation or greatly reduced when intensity modulation is present.

**17 Claims, 6 Drawing Sheets**





10
RF_OUT
RECEIVER
16
DIFFERENTIATOR
24
22
PHOTODETECTOR
OPTICAL FILTER
20
14
OPTICAL FIBER
DFB LASER
12
RF_IN


FIG. 1

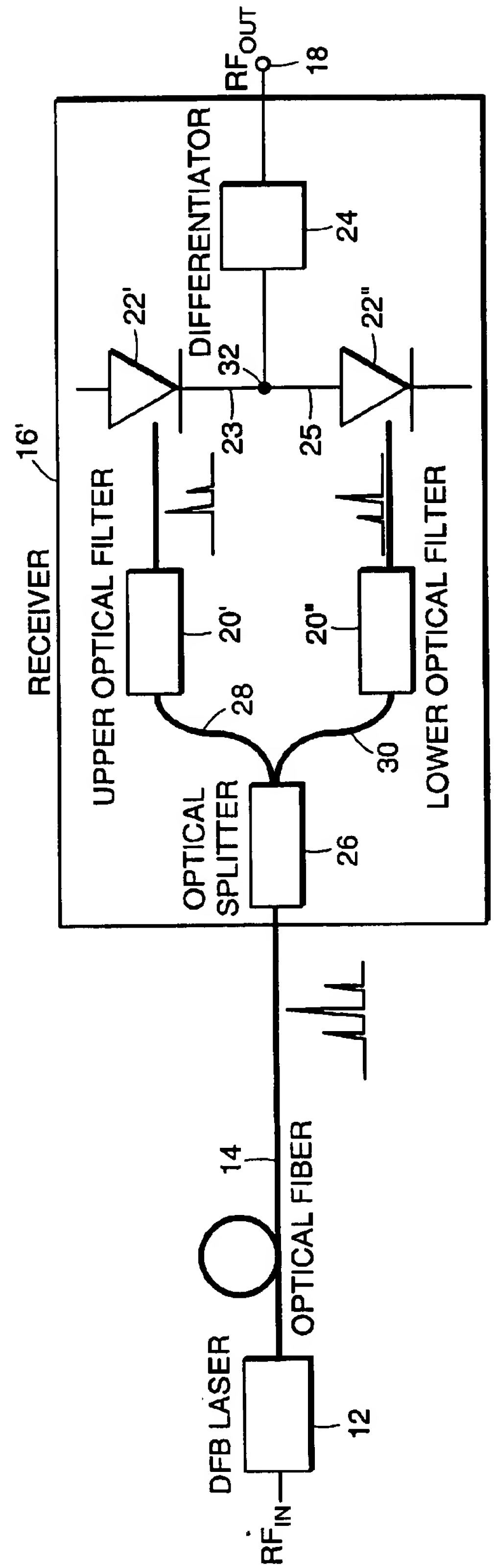
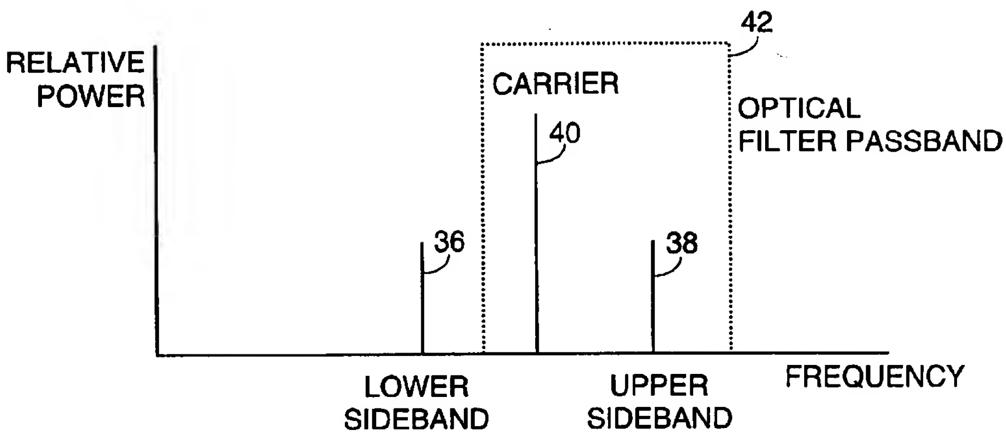
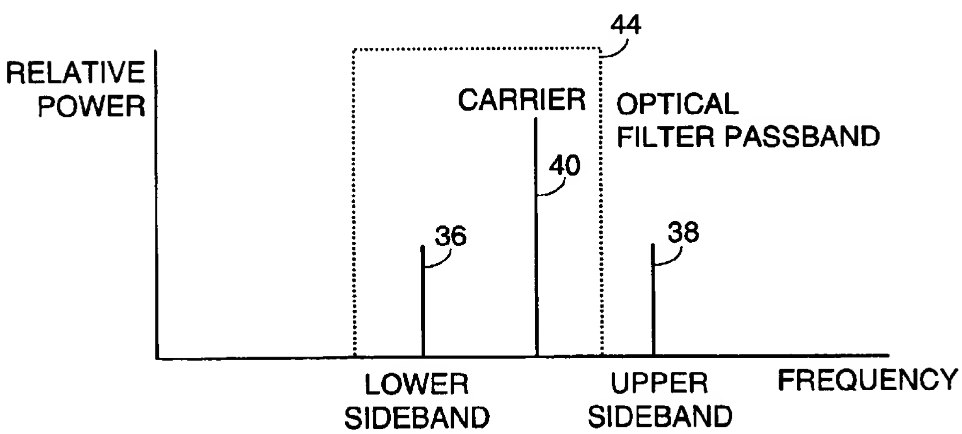

RF_OUT
18
RECEIVER
16'
DIFFERENTIATOR
24
22'
32
23
25
22"
UPPER OPTICAL FILTER
20'
20"
LOWER OPTICAL FILTER
28
30
OPTICAL SPLITTER
26
14
OPTICAL FIBER
DFB LASER
12
RF_IN

FIG. 2



42
RELATIVE
POWER
CARRIER
OPTICAL
FILTER PASSBAND
40
36
38
LOWER
SIDEBAND
UPPER
SIDEBAND
FREQUENCY


FIG. 3A



44
RELATIVE
POWER
CARRIER
OPTICAL
FILTER PASSBAND
40
36
38
LOWER
SIDEBAND
UPPER
SIDEBAND
FREQUENCY


FIG. 3B

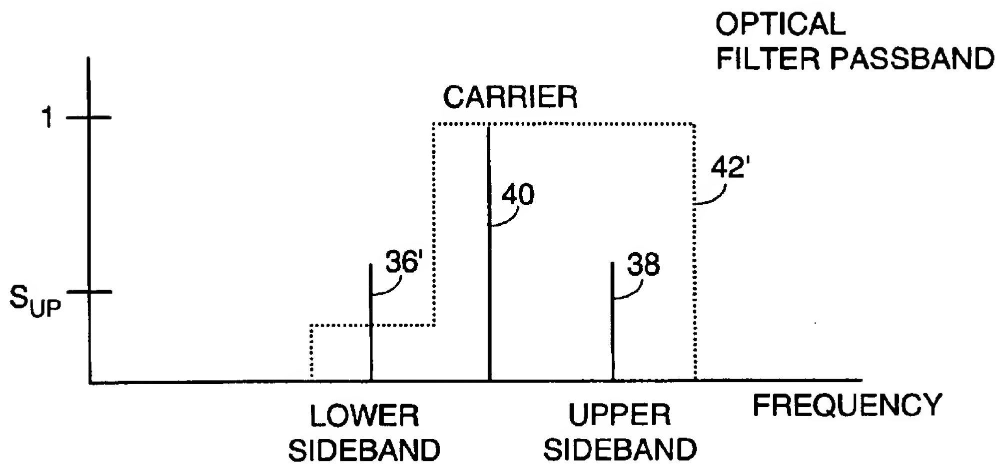

OPTICAL
FILTER PASSBAND
CARRIER
1
42'
40
36'
38
$S_{UP}$
FREQUENCY
LOWER
SIDEBAND
UPPER
SIDEBAND

FIG. 3C

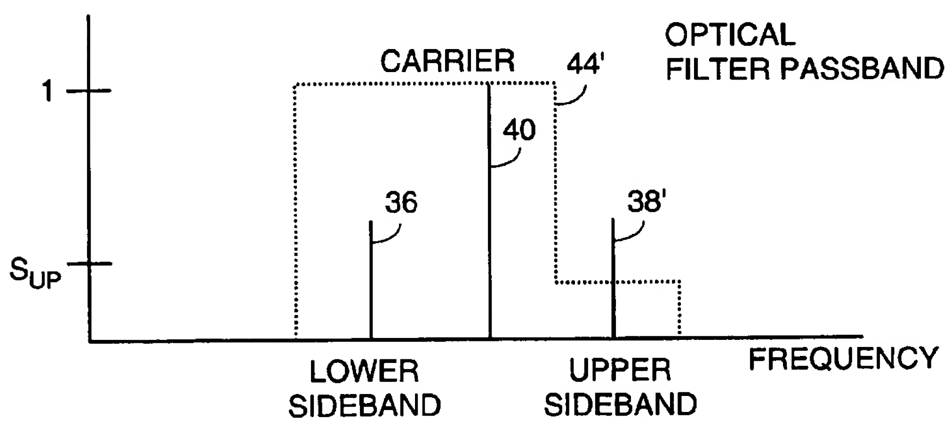
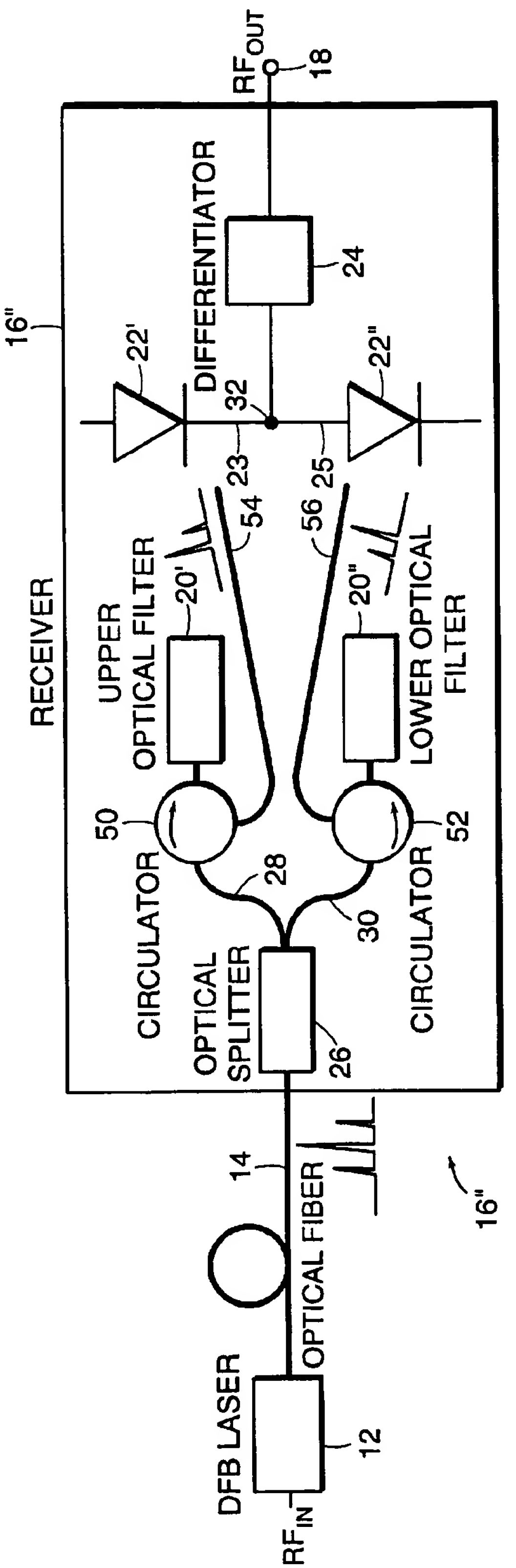

OPTICAL
FILTER PASSBAND
CARRIER
44'
1
40
36
38'
$S_{UP}$
FREQUENCY
LOWER
SIDEBAND
UPPER
SIDEBAND

FIG. 3D



RF OUT
18
RECEIVER
16"
DIFFERENTIATOR
24
22'
32
22"
23
25
54
56
UPPER OPTICAL FILTER
20'
20"
LOWER OPTICAL FILTER
50
52
CIRCULATOR
CIRCULATOR
28
30
OPTICAL SPLITTER
26
14
OPTICAL FIBER
16"
DFB LASER
12
RF IN


FIG. 4

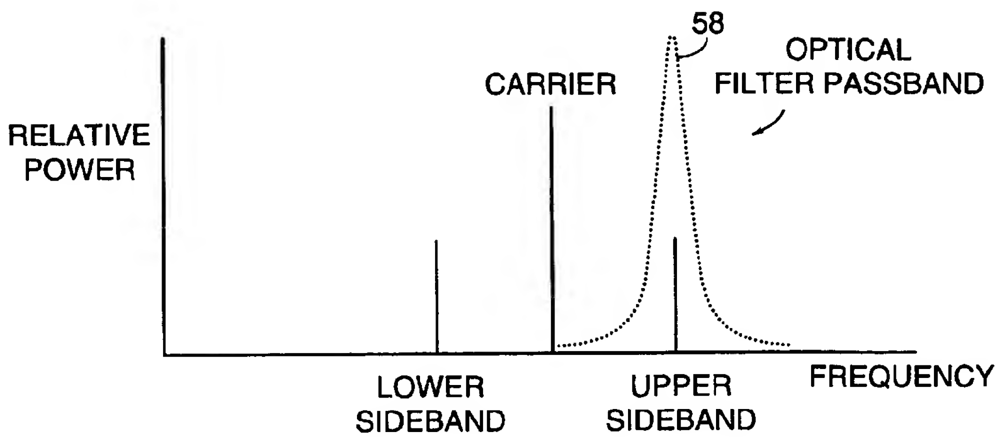

58
OPTICAL
FILTER PASSBAND
CARRIER
RELATIVE
POWER
LOWER
SIDEBAND
UPPER
SIDEBAND
FREQUENCY

FIG. 5A

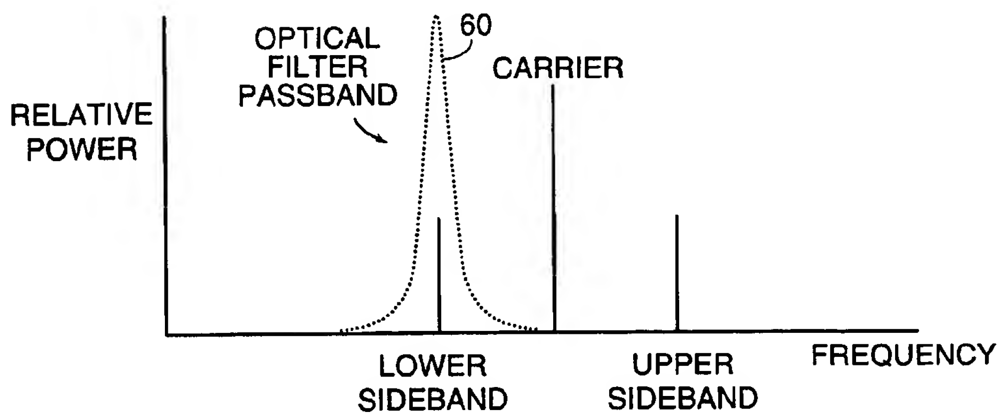

OPTICAL
FILTER
PASSBAND
60
CARRIER
RELATIVE
POWER
LOWER
SIDEBAND
UPPER
SIDEBAND
FREQUENCY

FIG. 5B

# ALL-OPTICAL ANALOG FM OPTICAL RECEIVER

## GOVERNMENT SUPPORT

This invention was made with government support under Contract Number F19628-95-C-0002 awarded by the Department of the Air Force. The government may have certain rights in the invention.

## FIELD OF THE INVENTION

The invention relates generally to an apparatus and method for an optical communications system, and in particular, to an analog frequency modulated (FM) optical receiver.

## BACKGROUND OF THE INVENTION

Communication systems based on optical technologies are becoming more common due to advantages over conventional wire-based communication systems. Although digital optical links can provide high data bandwidths, in some implementations analog optical links are preferred, for example where providing digital processing capability at the transmitter is impractical.

An analog optical link can exhibit an unacceptable noise figure (NF) and an unacceptable spurious-signal-free dynamic range (SFDR). For example, conventional Mach-Zehnder modulated optical links are subject in general to second order harmonics and third order difference intermodulation products. Thus a need exists for a simple and inexpensive high performance analog optical link having a low noise figure and a high SFDR.

## SUMMARY OF THE INVENTION

The present invention relates to an apparatus and method for all-optical, frequency modulated (FM) communication. The method and apparatus make use of a balanced receiver configuration having a set of optical filters. An optical beam splitter provides an optical signal to two distinct optical filters. One optical filter removes the upper sideband and the other optical filter removes the lower sideband. The filtered signals are detected and their photocurrents subtracted before the resulting electrical signal is provided to a differentiator for demodulation. Laser relative intensity noise (RIN) and second order harmonics are thereby eliminated. In addition, third order distortion is eliminated when no intensity modulation (IM) is present, or greatly reduced when IM is present, As a result, this analog optical link has a low noise figure and a high spurious-signal-free dynamic range.

The present invention features a transmitter for an optical communication system which includes a FM optical signal source and an optical filter in communication with the FM source. The optical filter produces a single sideband optical signal. In one embodiment the transmitter also includes a beamsplitter and a second optical filter. The beamsplitter is in optical communication with the FM optical signal source and has a first and second beam output. Each optical filter is in communication with a respective beam output and removes one sideband of the FM optical signal.

The invention also features a receiver for an optical communication system which includes an optical filter, a photodetector in optical communication with the filter, and a differentiator in electrical communication with the photodetector. The optical filter removes one sideband of a FM optical signal to produce a single sideband FM optical signal and the differentiator produces a demodulated electrical signal in response to the single sideband FM optical signal. In one embodiment the receiver also includes a beamsplitter and a second optical filter. The beamsplitter is in optical communication with the FM optical signal source and has a first and second beam output. Each optical filter is in communication with a respective beam output and produces a respective single sideband FM optical signal in response to the FM optical signal.

The invention also features a communication system which includes a FM optical signal source, an optical filter in optical communication with the FM optical signal source, a photodetector in optical communication with the filter and a differentiator in electrical communication with the photodetector. The differentiator produces a demodulated FM electrical signal in response to the FM optical signal. In one embodiment the system also includes a beam splitter, a second filter and a second photodetector in electrical communication with the differentiator. The differentiator produces a demodulated electrical signal in response to the detected electrical signals from the photodetectors.

## BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, features and advantages of the invention will become apparent from the following more particular description of preferred embodiments of the invention, as illustrated in the accompanying drawings. The drawings are not necessarily to scale, emphasis instead being placed on illustrating the principles of the present invention.

FIG. **1** is a functional block diagram illustrating one embodiment of an all-optical FM analog link;

FIG. **2** is a functional block diagram illustrating another embodiment of an all-optical FM analog link;

FIGS. *3a–3d* are diagrams of the filtered optical spectrums according to the invention;

FIG. **4** is a functional block diagram of an embodiment of an all-optical FM analog link using Fabry-Perot filters;

FIGS. *5a* and *5b* are diagrams of the filtered optical spectrums of the embodiment of FIG. 4.

## DESCRIPTION OF THE INVENTION

Referring to FIG. **1**, an all-optical FM link **10** includes a laser source **12** which can be directly modulated, an optical fiber **14** and a receiver **16**. Preferably, the laser **12** is a distributed feedback (DFB) laser (e.g. KBK Inc., New York, N.Y., DFB laser model no. KLED1563BTB which has a FM response efficiency of 50–500 MHz/mA, depending on the modulation frequency, and a bandwidth up to 3 GHz) which is directly modulated by a RF signal ($RF_{in}$). The resulting modulated optical signal includes both intensity modulation (IM) and frequency modulation (FM). The receiver includes an optical filter **20**, a photodetector **22** and a differentiator **24**. The optical filter **20** suppresses one sideband of the optical signal and passes both the carrier and the other sideband. As an example, a fiber grating filter can be used in a fiber-based receiver. Generally, any transmissive optical filter with the proper spectral characteristics can be used. Without the optical filter **20** the FM modulation is canceled and only the IM is detected. Demodulation of the electrical signal generated by the photodetector **22** is accomplished with the differentiator **24** and results in an output RF signal ($RF_{out}$) at the receiver output terminal **18**.

Other lasers that can be directly modulated and have a single longitudinal mode can be used in place of the conventional DFB laser **12**. Semiconductor lasers which satisfy

these requirements include, but are not limited to, distributed Bragg reflector (DBR) lasers, external cavity lasers and multiple quantum well (MQW) lasers. In addition, some solid state lasers (e.g., Nd:YAG lasers) can be directly modulated, although the modulation efficiency and modulation bandwidth are typically low.

Unlike a coherent analog FM link, the all-optical FM analog link **10** does not require an additional laser source or strict optical frequency tracking, although the optical frequency must be stable enough to allow proper optical filtering. Laser relative intensity noise (RIN), however, is still present in the demodulated signal ($RF_{out}$)

Referring to FIG. **2**, an all-optical FM analog link **10'** having a balanced receiver configuration includes a DFB laser **12**, an optical fiber **14** and a dual receiver **16'**. The dual receiver **16'** includes a beamsplitter **26**, an upper optical filter **20'**, a lower optical filter **20'**, two photodetectors **22'** and **22"**, and a differentiator **24**. Modulated light from the optical fiber **14** is split into an upper optical path **28** and a lower optical path **30**. The optical paths **28**, **30** can include, but are not limited to, optical fiber or a free space path defined by bulk optical components. Light in the upper path **28** passes through the upper filter **20'** where the lower sideband is removed from the modulated optical signal. The upper detector **22'** receives the filtered single sideband optical signal and generates a corresponding modulated electrical signal at the detector output **23**. Similarly, light in the lower path **30** passes through the lower optical filter **20'** where the upper sideband is removed from the modulated optical signal. The second detector **22'** receives this second filtered single sideband optical signal and generates a corresponding modulated electrical signal at the detector output **25**. A resulting sum modulated signal at node **32** is differentiated by the differentiator **24** to generate a demodulated electrical signal ($RF_{out}$) at the receiver output **18**.

FIG. **3***a* illustrates how the upper optical filter **20'** removes the lower sideband **36** and transmits the upper sideband **38** and carrier **40** which lie within the passband **42** of the filter **20'**. Similarly, FIG. **3***b* illustrates how the lower optical filter **20"** removes the upper sideband **38** and transmits the lower sideband **36** and carrier **40** which lie within the passband **44** of the filter **20"**.

The contribution to the photocurrents generated by the detectors **22'**, **22"** due to RIN are equal because the upper RIN sideband is the same as the lower RIN sideband. Thus one advantage of the balanced receiver configuration **10'** is the elimination of RIN. Shot noise and thermal noise in the two paths are not correlated, however, so subtraction of the photocurrents from the detectors **22'**, **22"** does not eliminate these noise components from the demodulated electrical signal $RF_{out}$. Instead, the shot noise and thermal noise present in each optical path **28**, **30** are incoherently summed. In addition, second order harmonics and third order distortion are eliminated when no IM is present. Even if IM exists, both second order harmonics and third order distortion are substantially reduced. As a result the balanced receiver configuration **10'** has a low noise figure and a high spurious-signal-free dynamic range.

The demodulated RF signal current is given by:

$$i_{sig} = K\Re P_S K_{FM} x_h(t) \tag{1}$$

where K is the efficiency of the differentiator **24**, $\Re$ is the photodetector responsivity, $P_S$ is the optical power, $K_{FM}$ is the frequency modulation index and $x_h(t)$ is the normalized RF input signal. The gain of the all-optical FM analog link **10'** is given by:

$$G = (\Re P_S)^2 (2\pi\delta_{FM})^2 \frac{R_{out}}{R_{in}} \tag{2}$$

where ($\delta_{FM}$ is the FM efficiency (MHz/mA) of the laser **12** and $R_{out}$ and $R_{in}$ are the output and input resistance, respectively.

Using the ideal filter model illustrated in FIGS. **3A** and **3B**, the noise figure is approximated by:

$$NF = \frac{\eta B R_{in}}{(\Re P_S)^2 \left(\frac{\delta_{FM}}{f_c}\right)^2} \tag{3}$$

where η is the receiver noise spectral density, B is the signal bandwidth and $f_c$ is the center frequency of the RF signal ($RF_{in}$).

The spurious-signal-free dynamic range can be calculated assuming a more realistic model of the upper optical filter **20'** and lower optical filter **20"**, respectively, as shown in FIGS. **3C** and **3D**. In particular, the passbands **42'**,**44'** result in suppressed sidebands **36'**,**38'** with non-zero power contributions $S_{up}$. In addition, the RF input signal ($RF_{in}$) is assumed to be a two-tone signal where the tones are at closely spaced RF frequencies. The spurious-signal-free dynamic range is given by:

$$SFDR = 4\left(\frac{(\Re P_S)^2}{\eta B}\right)^{\frac{2}{3}} \frac{(1-S_{up})^2}{(8C_{IM}^2(1-S_{up}^2)+S_{up}(1-S_{up}))^{\frac{2}{3}}} \tag{4}$$

where

$$C_{IM} = \frac{2\pi f_c m}{K_{FM}}$$

and m is the intensity modulation index. While this spurious-signal-free dynamic range depends on the relative values of the FM and AM modulation efficiencies, it will typically be substantially better than conventional links utilizing Mach-Zehnder modulators.

Referring to FIG. **4**, another embodiment of a balanced receiver configuration **16"** includes an upper optical circulator **50** and lower optical circulator **52** (e.g., Kaifa Technology, Sunnyvale, Calif., optical circulator model no. CIR5-M which has a minimum isolation between ports of 40 dB). Modulated light from the laser **12** transmitted through the optical fiber **14** is split into the upper and lower optical paths **28** and **30**, respectively. Light in the upper path **28** passes through the upper optical circulator **50** and is reflected from the upper optical filter **20'** except for the lower sideband which is transmitted through the filter **20'** and lost. The reflected optical signal having a single sideband enters the upper optical circulator **50** where it is directed into an upper detector optical path **54** and onto the upper detector **22'**. Similarly, light in the lower path **30** passes through the lower optical circulator **52** and is reflected from the lower optical filter **20"** except for the upper sideband which is transmitted through the filter **20"** and lost. This second reflected optical signal also has a single (opposite) sideband and enters the lower optical circulator **52** where it is directed into a lower detector optical path **56** and onto the lower detector **22"**. As described in the previous embodiment, a demodulated electrical signal ($RF_{out}$) is generated at the receiver output **18**. This configuration, however, avoids the

carrier attenuation resulting from the transmissive optical filters **20'**, **20"** of the previous embodiment.

The reflective filters **20'**, **20"** can be the Fabry-Perot type (e.g., Micron Optics, Inc., Atlanta, Ga., tunable filter and controller model no. FFP-TF 1550-050M200-5 for a wavelength of 1550 nm and having a free spectral range of approximately 10 GHz and a finesse of approximately 200). FIGS. **5A** and **5B** illustrate how the narrow passbands **58, 60** of Fabry-Perot filters transmit a single sideband so that it is removed from the optical signals in the embodiment shown in FIG. **4**. Nearly all of the light outside the passbands **58, 60** is reflected back to the optical circulators **50, 52**.

## EQUIVALENTS

While the invention has been particularly shown and described with reference to specific preferred embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims.

What is claimed is:

**1**. A communication system comprising:

a first single sideband optical filter having an optical input and an optical output, said optical input adapted to receive a FM optical signal;

a first photodetector having an optical input in optical communication with said optical output of said first filter and having an electrical output;

a second single sideband optical filter having an optical input and an optical output, said optical input adapted to receive said FM optical signal;

a second photodetector having an optical input in optical communication with said optical output of said second filter and having an electrical output; and

a differentiator having an electrical input in electrical communication with said electrical outputs of said first and second photodetectors,

wherein said differentiator produces a demodulated electrical signal in response to said FM optical signal.

**2**. The communication system of claim **1** wherein said first optical filter comprises:

an optical circulator having an optical input, an optical output and an etalon port, said optical circulator optical input in optical communication with said optical input of said first filter,

wherein said FM optical signal at said optical circulator input is transmitted out said optical circulator etalon port; and

a Fabry-Perot etalon having an optical input in optical communication with said optical circulator etalon port,

wherein said FM optical signal from said optical circulator etalon port is at least partially reflected from said Fabry-Perot etalon back into said optical circulator etalon port and out from said optical circulator output.

**3**. The communication system of claim **1** further comprising a FM optical signal source generating said optical signal.

**4**. The transmitter of claim **3** wherein said FM optical signal source comprises a distributed feedback laser.

**5**. The transmitter of claim **1** wherein said first optical filter comprises a Fabry-Perot filter.

**6**. The transmitter of claim **1** wherein said first optical filter comprises a fiber grating filter.

**7**. The communication system of claim **1**, wherein said first and second optical filters each have a bandwidth sufficient to transmit a carrier and a sideband of said optical signal.

**8**. The second photodetector of claim **1** further comprising an electrical input in communication with the electrical output of the first photodetector.

**9**. A method of transmitting an optical signal comprising the steps of:

providing a FM optical signal having a carrier and two sidebands;

optically filtering said FM optical signal to produce a first single sideband FM optical signal with the upper sideband removed;

optically filtering said FM optical signal to produce a second single sideband FM optical signal with the lower sideband removed; and

combining the first single sideband signal and the second single sideband signal, thereby reducing relative intensity noise in said FM optical signal.

**10**. A communication system comprising:

a FM optical signal source producing a FM optical signal at an optical output;

a beam splitter having an optical input in optical communication with said optical output of said FM optical signal source and having a first beam output and a second beam output;

a first optical filter having an optical input in optical communication with said first beam output and having an optical output,

wherein said first optical filter produces a first single sideband FM optical signal in response to said FM optical signal;

a second optical filter having an optical input in optical communication with said second beam output and having an optical output,

wherein said second optical filter produces a second single sideband FM optical signal in response to said FM optical signal;

a first photodetector having an optical input in optical communication with said first filter optical output and having an electrical output,

wherein said first photodetector produces a first detected electrical signal in response to said first single sideband FM optical signal;

a second photodetector having an optical input in optical communication with said second filter optical output and having an electrical output,

wherein said second photodetector produces a second detected electrical signal in response to said second single sideband FM optical signal; and

a differentiator having an electrical input in electrical communication with said first and second photodetector electrical outputs,

wherein said differentiator produces a demodulated electrical signal in response to said first and second detected electrical signals.

**11**. The communication system of claim **10** wherein said FM optical signal source comprises a distributed feedback laser.

**12**. A method of communication comprising the steps of:

providing a FM optical signal having a lower sideband, an upper sideband and a carrier;

splitting said FM optical signal to produce a first signal beam and a second signal beam;

optically filtering said first signal beam to remove said lower sideband to produce a first filtered beam;

optically filtering said second signal beam to remove said upper sideband to produce a second filtered beam;

detecting said first filtered beam to produce a first detected signal;

detecting said second filtered beam to produce a second detected signal;

combining said first and second detected signals to produce a combined signal; and

differentiating said combined signal to produce a demodulated signal.

13. A transmitter for an optical communication system comprising:

a FM optical signal source producing a FM optical signal at an optical output;

a beam splitter having an optical input in optical communication with said optical output of said FM optical signal source and having a first beam output and a second beam output;

a first optical filter having an optical input in optical communication with said first beam output,

wherein said first optical filter removes one sideband of said FM optical signal to produce a first single sideband FM optical signal; and

a second optical filter having an optical input in optical communication with said second beam output,

wherein said second optical filter removes one sideband of said FM optical signal to produce a second single sideband FM optical signal.

14. The transmitter of claim 13 wherein said FM optical signal source comprises a distributed feedback laser.

15. A method of transmitting an optical signal comprising the steps of:

providing a FM optical signal having a lower sideband, an upper sideband and a carrier;

splitting said FM optical signal to produce a first signal beam and a second signal beam;

optically filtering said first signal beam to remove said lower sideband to produce a first filtered beam; and

optically filtering said second signal beam to remove said upper sideband to produce a second filtered beam.

16. A receiver for an optical communication system comprising:

a beam splitter having an optical input, a first beam output and a second beam output;

a first optical filter having an optical output in optical communication with said first beam output and having an optical output,

wherein said first optical filter produces a first single sideband FM optical signal in response to a FM optical signal received at said beam splitter optical input;



a second optical filter having an optical output in optical communication with said second beam output and having an optical output,

wherein said second optical filter produces a second single sideband FM optical signal in response to said FM optical signal;

a first photodetector having an optical input in optical communication with said first filter optical output and having an electrical output,

wherein said first photodetector produces a first detected electrical signal in response to said first single sideband FM optical signal;

a second photodetector having an optical input in optical communication with said second filter optical output and having an electrical output,

wherein said second photodetector produces a second detected electrical signal in response to said second single sideband FM optical signal; and

a differentiator having an electrical input in electrical communication with said first and second photodetector electrical outputs,

wherein said differentiator produces a demodulated electrical signal in response to said first and second detected electrical signals.

17. A method of receiving an optical signal comprising the steps of:

splitting a FM optical signal having a lower sideband, an upper sideband and a carrier to produce a first signal beam and a second signal beam;

optically filtering said first signal beam to remove said lower sideband to produce a first single sideband FM optical signal;

optically filtering said second signal beam to remove said upper sideband to produce a second single sideband FM optical signal;

detecting said first single sideband FM optical signal to produce a first detected electrical signal;

detecting said second single sideband FM optical signal to produce a second detected electrical signal;

combining said first and second detected electrical signals to produce a combined electrical signal; and

differentiating said combined electrical signal to produce a demodulated signal.

* * * * *

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(12) **United States Patent**
**Taylor**

(10) **Patent No.:** US 6,359,716 B1
(45) **Date of Patent:** Mar. 19, 2002

(54) **ALL-OPTICAL ANALOG FM OPTICAL RECEIVER**

(75) Inventor: **Robert B. Taylor**, Woburn, MA (US)

(73) Assignee: **Massachusetts Institute of Technology**, Cambridge, MA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/256,954**

(22) Filed: **Feb. 24, 1999**

(51) **Int. Cl.**[7] .................... **H04B 10/06**
(52) **U.S. Cl.** .................... **359/189**; 359/193; 359/195
(58) **Field of Search** .................... 359/189, 193, 359/195

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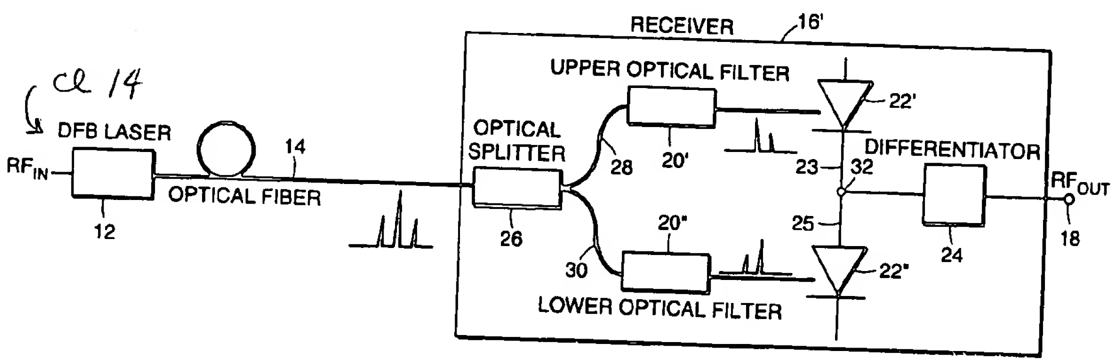
*Primary Examiner*—Leslie Pascal
*Assistant Examiner*—Hanh Phan
(74) *Attorney, Agent, or Firm*—Testa, Hurwitz & Thibeault, LLP

(57) **ABSTRACT**

Method and apparatus for an analog FM optical link having a low noise figure and a high spurious-free dynamic range. In one embodiment, the apparatus includes a FM DFB laser and a balanced receiver. The balanced receiver includes an optical splitter to split the received beam into two optical paths. Each of the two paths includes an optical filter and a photodetector. A differentiator coupled to the electrical output of the photodetectors produces a demodulated electrical signal in response to the RF signal used to modulate the DFB laser. This configuration can eliminate the laser relative intensity noise and second order harmonics. In addition, third order distortion is eliminated when there is no intensity modulation or greatly reduced when intensity modulation is present.

**17 Claims, 6 Drawing Sheets**




01/14/2004, EAST Version: 1.4.1

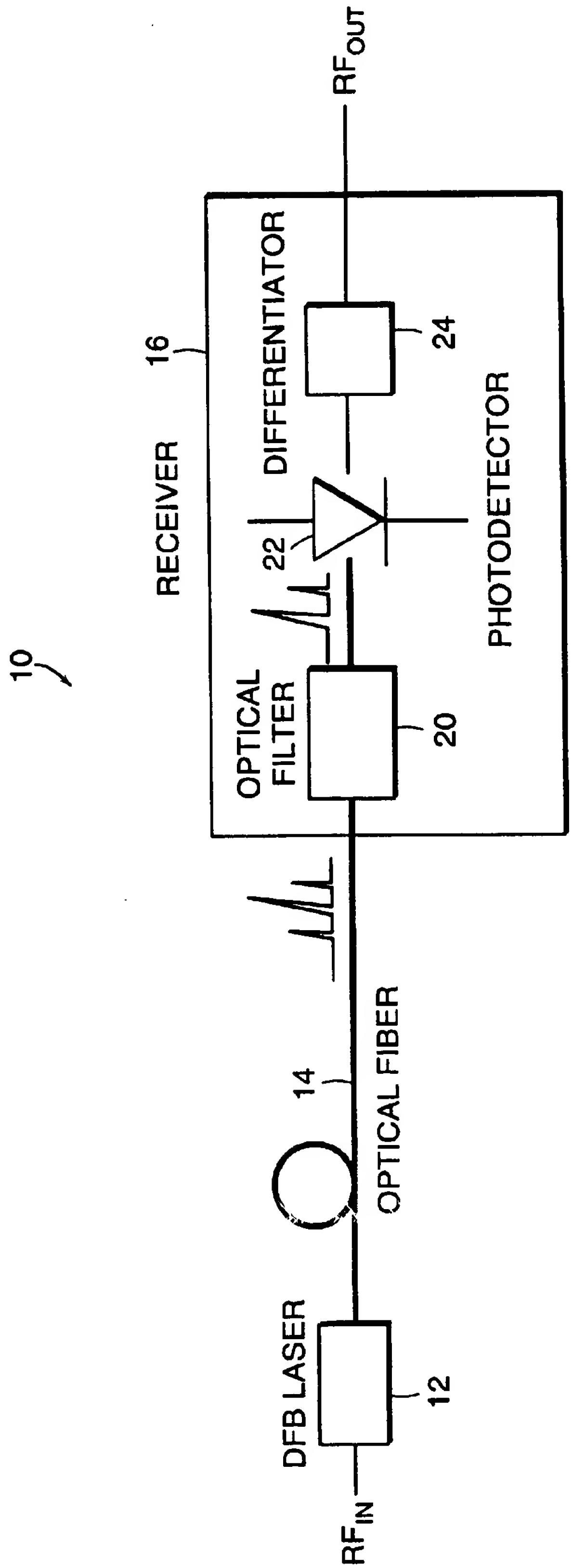

RF$_{OUT}$
16
RECEIVER
DIFFERENTIATOR
24
22
PHOTODETECTOR
10
OPTICAL FILTER
20
14
OPTICAL FIBER
DFB LASER
12
RF$_{IN}$

FIG. 1

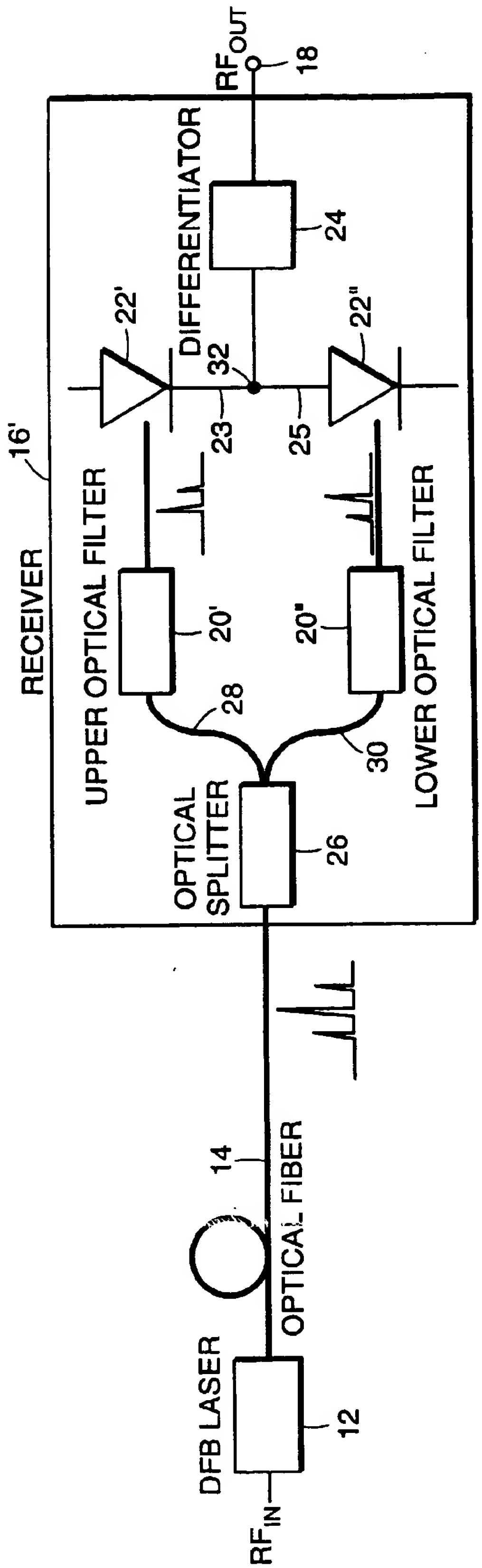

RF_OUT
18
DIFFERENTIATOR
24
22'
22"
32
23
25
16'
RECEIVER
UPPER OPTICAL FILTER
LOWER OPTICAL FILTER
20'
20"
28
30
OPTICAL SPLITTER
26
14
OPTICAL FIBER
DFB LASER
12
RF_IN

FIG. 2

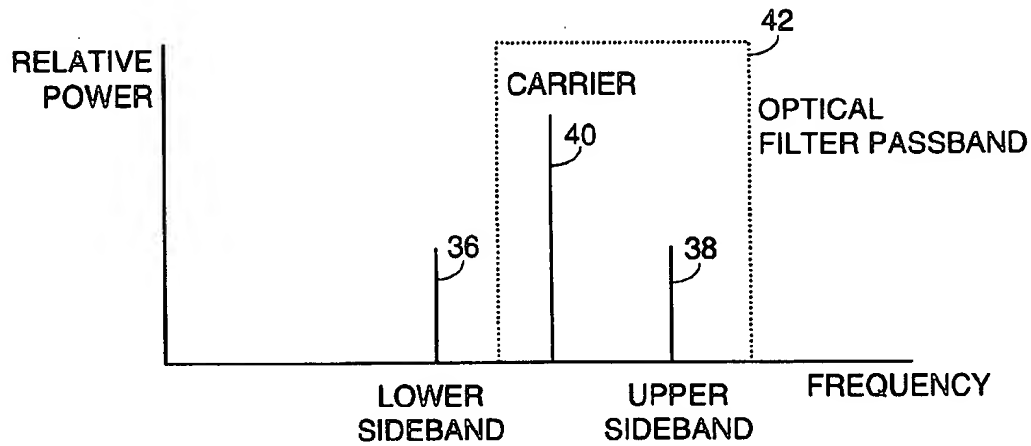

42
RELATIVE POWER
CARRIER
OPTICAL FILTER PASSBAND
40
36
38
LOWER SIDEBAND
UPPER SIDEBAND
FREQUENCY

FIG. 3A

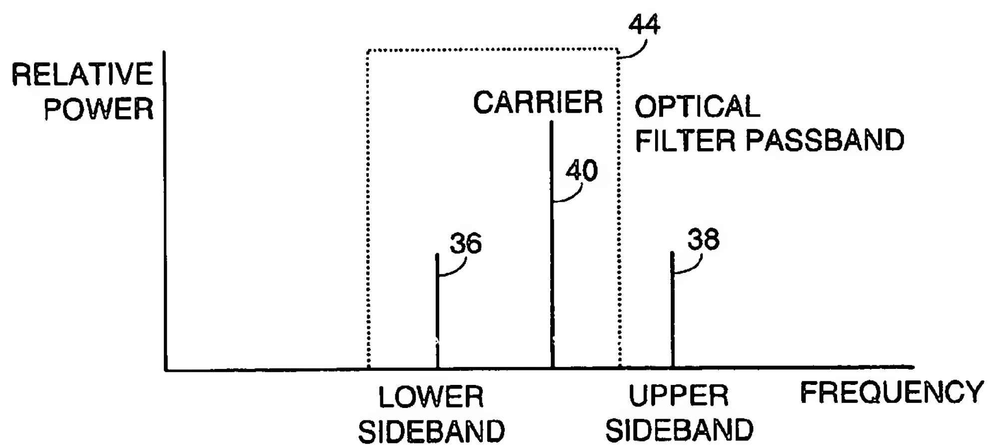

44
RELATIVE POWER
CARRIER
OPTICAL FILTER PASSBAND
40
36
38
LOWER SIDEBAND
UPPER SIDEBAND
FREQUENCY

FIG. 3B

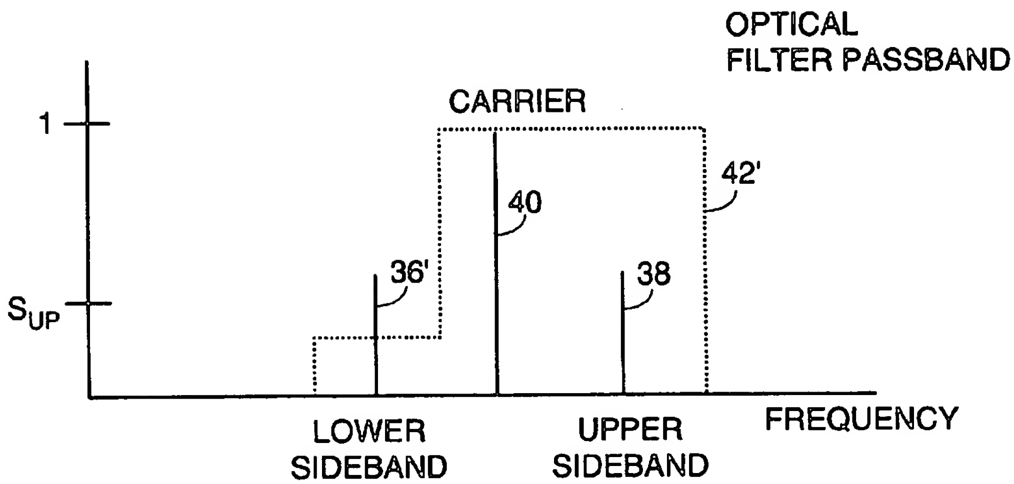

OPTICAL
FILTER PASSBAND
CARRIER
1
42'
40
36'
38
$S_{UP}$
FREQUENCY
LOWER
SIDEBAND
UPPER
SIDEBAND

FIG. 3C

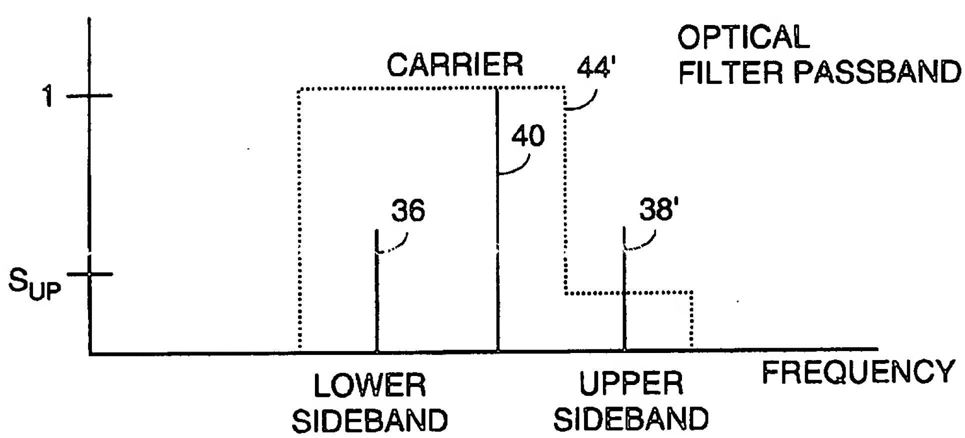

OPTICAL
FILTER PASSBAND
CARRIER
44'
1
40
36
38'
$S_{UP}$
FREQUENCY
LOWER
SIDEBAND
UPPER
SIDEBAND

FIG. 3D

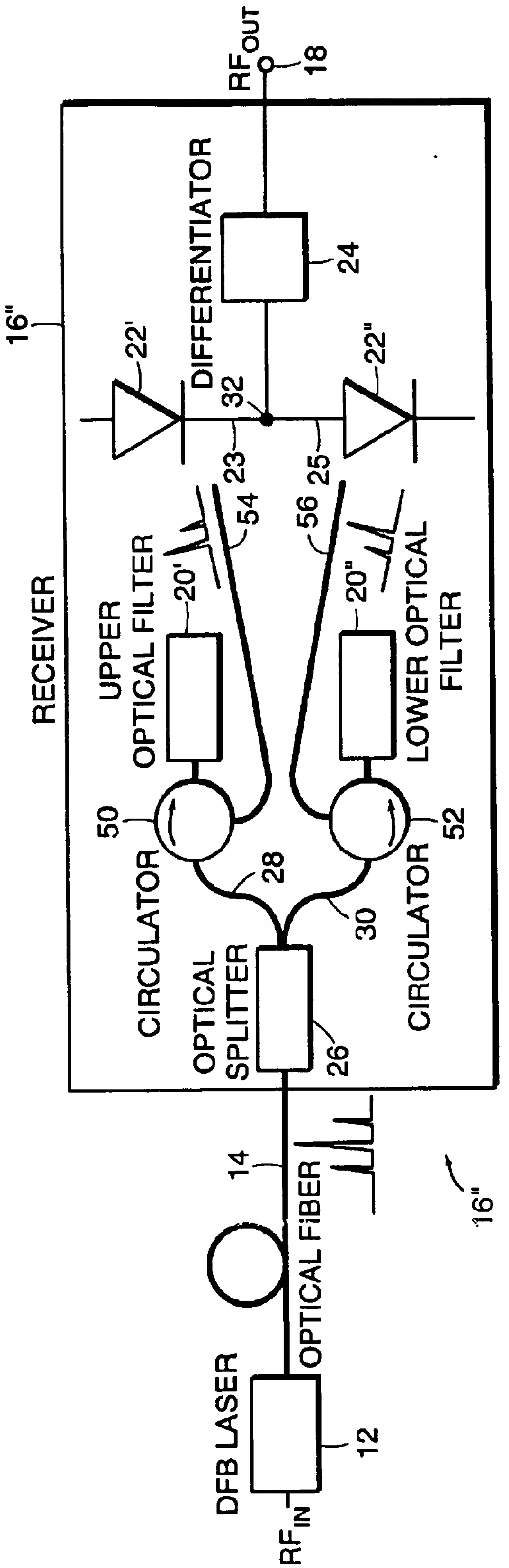

RF_OUT
18
DIFFERENTIATOR
24
16"
22'
32
22"
23
25
RECEIVER
54
56
UPPER OPTICAL FILTER
20'
20"
LOWER OPTICAL FILTER
50
52
CIRCULATOR
28
30
CIRCULATOR
OPTICAL SPLITTER
26
14
OPTICAL FiBER
16"
DFB LASER
12
RF_IN

FIG. 4

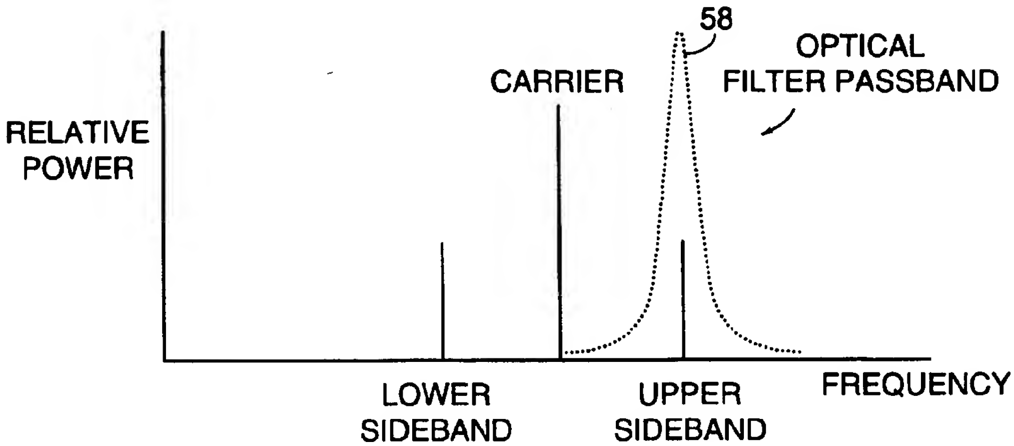

58
OPTICAL
FILTER PASSBAND
CARRIER
RELATIVE
POWER
LOWER
SIDEBAND
UPPER
SIDEBAND
FREQUENCY

FIG. 5A

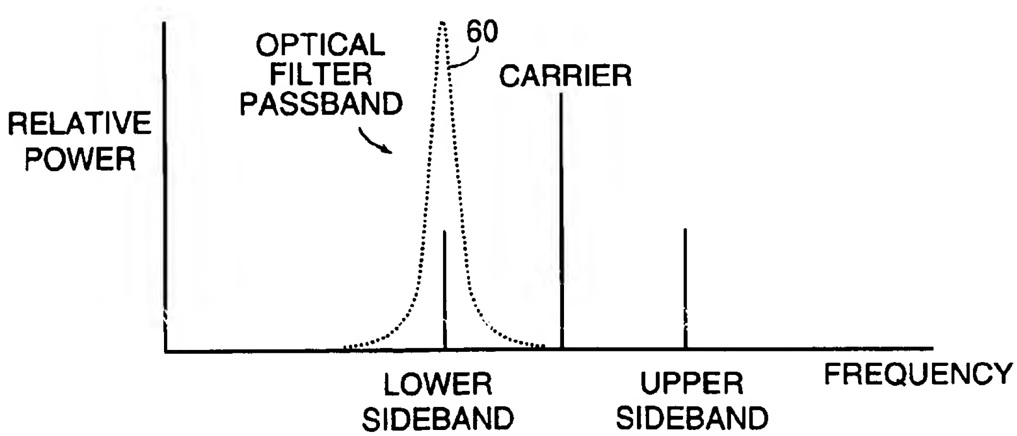

OPTICAL
FILTER
PASSBAND
60
CARRIER
RELATIVE
POWER
LOWER
SIDEBAND
UPPER
SIDEBAND
FREQUENCY

FIG. 5B

# ALL-OPTICAL ANALOG FM OPTICAL RECEIVER

## GOVERNMENT SUPPORT

This invention was made with government support under Contract Number F19628-95-C-0002 awarded by the Department of the Air Force. The government may have certain rights in the invention.

## FIELD OF THE INVENTION

The invention relates generally to an apparatus and method for an optical communications system, and in particular, to an analog frequency modulated (FM) optical receiver.

## BACKGROUND OF THE INVENTION

Communication systems based on optical technologies are becoming more common due to advantages over conventional wire-based communication systems. Although digital optical links can provide high data bandwidths, in some implementations analog optical links are preferred, for example where providing digital processing capability at the transmitter is impractical.

An analog optical link can exhibit an unacceptable noise figure (NF) and an unacceptable spurious-signal-free dynamic range (SFDR). For example, conventional Mach-Zehnder modulated optical links are subject in general to second order harmonics and third order difference intermodulation products. Thus a need exists for a simple and inexpensive high performance analog optical link having a low noise figure and a high SFDR.

## SUMMARY OF THE INVENTION

The present invention relates to an apparatus and method for all-optical, frequency modulated (FM) communication. The method and apparatus make use of a balanced receiver configuration having a set of optical filters. An optical beam splitter provides an optical signal to two distinct optical filters. One optical filter removes the upper sideband and the other optical filter removes the lower sideband. The filtered signals are detected and their photocurrents subtracted before the resulting electrical signal is provided to a differentiator for demodulation. Laser relative intensity noise (RIN) and second order harmonics are thereby eliminated. In addition, third order distortion is eliminated when no intensity modulation (IM) is present, or greatly reduced when IM is present, As a result, this analog optical link has a low noise figure and a high spurious-signal-free dynamic range.

The present invention features a transmitter for an optical communication system which includes a FM optical signal source and an optical filter in communication with the FM source. The optical filter produces a single sideband optical signal. In one embodiment the transmitter also includes a beamsplitter and a second optical filter. The beamsplitter is in optical communication with the FM optical signal source and has a first and second beam output. Each optical filter is in communication with a respective beam output and removes one sideband of the FM optical signal.

The invention also features a receiver for an optical communication system which includes an optical filter, a photodetector in optical communication with the filter, and a differentiator in electrical communication with the photodetector. The optical filter removes one sideband of a FM optical signal to produce a single sideband FM optical signal and the differentiator produces a demodulated electrical signal in response to the single sideband FM optical signal. In one embodiment the receiver also includes a beamsplitter and a second optical filter. The beamsplitter is in optical communication with the FM optical signal source and has a first and second beam output. Each optical filter is in communication with a respective beam output and produces a respective single sideband FM optical signal in response to the FM optical signal.

The invention also features a communication system which includes a FM optical signal source, an optical filter in optical communication with the FM optical signal source, a photodetector in optical communication with the filter and a differentiator in electrical communication with the photodetector. The differentiator produces a demodulated FM electrical signal in response to the FM optical signal. In one embodiment the system also includes a beam splitter, a second filter and a second photodetector in electrical communication with the differentiator. The differentiator produces a demodulated electrical signal in response to the detected electrical signals from the photodetectors.

## BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, features and advantages of the invention will become apparent from the following more particular description of preferred embodiments of the invention, as illustrated in the accompanying drawings. The drawings are not necessarily to scale, emphasis instead being placed on illustrating the principles of the present invention.

FIG. 1 is a functional block diagram illustrating one embodiment of an all-optical FM analog link;

FIG. 2 is a functional block diagram illustrating another embodiment of an all-optical FM analog link;

FIGS. *3a–3d* are diagrams of the filtered optical spectrums according to the invention;

FIG. 4 is a functional block diagram of an embodiment of an all-optical FM analog link using Fabry-Perot filters;

FIGS. *5a* and *5b* are diagrams of the filtered optical spectrums of the embodiment of FIG. 4.

## DESCRIPTION OF THE INVENTION

Referring to FIG. 1, an all-optical FM link **10** includes a laser source **12** which can be directly modulated, an optical fiber **14** and a receiver **16**. Preferably, the laser **12** is a distributed feedback (DFB) laser (e.g. KBK Inc., New York, N.Y., DFB laser model no. KLED1563BTB which has a FM response efficiency of 50–500 MHz/mA, depending on the modulation frequency, and a bandwidth up to 3 GHz) which is directly modulated by a RF signal ($RF_{in}$). The resulting modulated optical signal includes both intensity modulation (IM) and frequency modulation (FM). The receiver includes an optical filter **20**, a photodetector **22** and a differentiator **24**. The optical filter **20** suppresses one sideband of the optical signal and passes both the carrier and the other sideband. As an example, a fiber grating filter can be used in a fiber-based receiver. Generally, any transmissive optical filter with the proper spectral characteristics can be used. Without the optical filter **20** the FM modulation is canceled and only the IM is detected. Demodulation of the electrical signal generated by the photodetector **22** is accomplished with the differentiator **24** and results in an output RF signal ($RF_{out}$) at the receiver output terminal **18**.

Other lasers that can be directly modulated and have a single longitudinal mode can be used in place of the conventional DFB laser **12**. Semiconductor lasers which satisfy

these requirements include, but are not limited to, distributed Bragg reflector (DBR) lasers, external cavity lasers and multiple quantum well (MQW) lasers. In addition, some solid state lasers (e.g., Nd:YAG lasers) can be directly modulated, although the modulation efficiency and modulation bandwidth are typically low.

Unlike a coherent analog FM link, the all-optical FM analog link **10** does not require an additional laser source or strict optical frequency tracking, although the optical frequency must be stable enough to allow proper optical filtering. Laser relative intensity noise (RIN), however, is still present in the demodulated signal ($RF_{out}$)

Referring to FIG. **2**, an all-optical FM analog link **10'** having a balanced receiver configuration includes a DFB laser **12**, an optical fiber **14** and a dual receiver **16'**. The dual receiver **16'** includes a beamsplitter **26**, an upper optical filter **20'**, a lower optical filter **20'**, two photodetectors **22'** and **22"**, and a differentiator **24**. Modulated light from the optical fiber **14** is split into an upper optical path **28** and a lower optical path **30**. The optical paths **28**, **30** can include, but are not limited to, optical fiber or a free space path defined by bulk optical components. Light in the upper path **28** passes through the upper filter **20'** where the lower sideband is removed from the modulated optical signal. The upper detector **22'** receives the filtered single sideband optical signal and generates a corresponding modulated electrical signal at the detector output **23**. Similarly, light in the lower path **30** passes through the lower optical filter **20'** where the upper sideband is removed from the modulated optical signal. The second detector **22'** receives this second filtered single sideband optical signal and generates a corresponding modulated electrical signal at the detector output **25**. A resulting sum modulated signal at node **32** is differentiated by the differentiator **24** to generate a demodulated electrical signal ($RF_{out}$) at the receiver output **18**.

FIG. **3***a* illustrates how the upper optical filter **20'** removes the lower sideband **36** and transmits the upper sideband **38** and carrier **40** which lie within the passband **42** of the filter **20'**. Similarly, FIG. **3***b* illustrates how the lower optical filter **20"** removes the upper sideband **38** and transmits the lower sideband **36** and carrier **40** which lie within the passband **44** of the filter **20"**.

The contribution to the photocurrents generated by the detectors **22'**, **22"** due to RIN are equal because the upper RIN sideband is the same as the lower RIN sideband. Thus one advantage of the balanced receiver configuration **10'** is the elimination of RIN. Shot noise and thermal noise in the two paths are not correlated, however, so subtraction of the photocurrents from the detectors **22'**, **22"** does not eliminate these noise components from the demodulated electrical signal $RF_{out}$. Instead, the shot noise and thermal noise present in each optical path **28**, **30** are incoherently summed. In addition, second order harmonics and third order distortion are eliminated when no IM is present. Even if IM exists, both second order harmonics and third order distortion are substantially reduced. As a result the balanced receiver configuration **10'** has a low noise figure and a high spurious-signal-free dynamic range.

The demodulated RF signal current is given by:

$$i_{sig} = K\Re P_S K_{FM} x_h(t) \tag{1}$$

where K is the efficiency of the differentiator **24**, $\Re$ is the photodetector responsivity, $P_S$ is the optical power, $K_{FM}$ is the frequency modulation index and $x_h(t)$ is the normalized RF input signal. The gain of the all-optical FM analog link **10'** is given by:

$$G = (\Re P_S)^2 (2\pi\delta_{FM})\frac{R_{out}}{R_{in}} \tag{2}$$

where ($\delta_{FM}$ is the FM efficiency (MHz/mA) of the laser **12** and $R_{out}$ and $R_{in}$ are the output and input resistance, respectively.

Using the ideal filter model illustrated in FIGS. **3A** and **3B**, the noise figure is approximated by:

$$NF = \frac{\eta B R_{in}}{(\Re P_S)^2\left(\frac{\delta_{FM}}{f_c}\right)^2} \tag{3}$$

where $\eta$ is the receiver noise spectral density, B is the signal bandwidth and $f_c$ is the center frequency of the RF signal ($RF_{in}$).

The spurious-signal-free dynamic range can be calculated assuming a more realistic model of the upper optical filter **20'** and lower optical filter **20"**, respectively, as shown in FIGS. **3C** and **3D**. In particular, the passbands **42'**,**44'** result in suppressed sidebands **36'**,**38'** with non-zero power contributions $S_{up}$. In addition, the RF input signal ($RF_{in}$) is assumed to be a two-tone signal where the tones are at closely spaced RF frequencies. The spurious-signal-free dynamic range is given by:

$$SFDR = 4\left(\frac{(\Re P_S)^2}{\eta B}\right)^{\frac{2}{3}} \frac{(1 - S_{up})^2}{(8C_{IM}^2(1 - S_{up}^2) + S_{up}(1 - S_{up}))^{\frac{2}{3}}} \tag{4}$$

where

$$C_{IM} = \frac{2\pi f_c m}{K_{FM}}$$

and m is the intensity modulation index. While this spurious-signal-free dynamic range depends on the relative values of the FM and AM modulation efficiencies, it will typically be substantially better than conventional links utilizing Mach-Zehnder modulators.

Referring to FIG. **4**, another embodiment of a balanced receiver configuration **16"** includes an upper optical circulator **50** and lower optical circulator **52** (e.g., Kaifa Technology, Sunnyvale, Calif., optical circulator model no. CIR5-M which has a minimum isolation between ports of 40 dB). Modulated light from the laser **12** transmitted through the optical fiber **14** is split into the upper and lower optical paths **28** and **30**, respectively. Light in the upper path **28** passes through the upper optical circulator **50** and is reflected from the upper optical filter **20'** except for the lower sideband which is transmitted through the filter **20'** and lost. The reflected optical signal having a single sideband enters the upper optical circulator **50** where it is directed into an upper detector optical path **54** and onto the upper detector **22'**. Similarly, light in the lower path **30** passes through the lower optical circulator **52** and is reflected from the lower optical filter **20"** except for the upper sideband which is transmitted through the filter **20"** and lost. This second reflected optical signal also has a single (opposite) sideband and enters the lower optical circulator **52** where it is directed into a lower detector optical path **56** and onto the lower detector **22"**. As described in the previous embodiment, a demodulated electrical signal ($RF_{out}$) is generated at the receiver output **18**. This configuration, however, avoids the

carrier attenuation resulting from the transmissive optical filters **20'**, **20"** of the previous embodiment.

The reflective filters **20'**, **20"** can be the Fabry-Perot type (e.g., Micron Optics, Inc., Atlanta, Ga., tunable filter and controller model no. FFP-TF 1550-050M200-5 for a wavelength of 1550 nm and having a free spectral range of approximately 10 GHz and a finesse of approximately 200). FIGS. **5A** and **5B** illustrate how the narrow passbands **58**, **60** of Fabry-Perot filters transmit a single sideband so that it is removed from the optical signals in the embodiment shown in FIG. **4**. Nearly all of the light outside the passbands **58**, **60** is reflected back to the optical circulators **50**, **52**.

## EQUIVALENTS

While the invention has been particularly shown and described with reference to specific preferred embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims.

What is claimed is:

1. A communication system comprising:

a first single sideband optical filter having an optical input and an optical output, said optical input adapted to receive a FM optical signal;

a first photodetector having an optical input in optical communication with said optical output of said first filter and having an electrical output;

a second single sideband optical filter having an optical input and an optical output, said optical input adapted to receive said FM optical signal;

a second photodetector having an optical input in optical communication with said optical output of said second filter and having an electrical output; and

a differentiator having an electrical input in electrical communication with said electrical outputs of said first and second photodetectors,

wherein said differentiator produces a demodulated electrical signal in response to said FM optical signal.

2. The communication system of claim 1 wherein said first optical filter comprises:

an optical circulator having an optical input, an optical output and an etalon port, said optical circulator optical input in optical communication with said optical input of said first filter,

wherein said FM optical signal at said optical circulator input is transmitted out said optical circulator etalon port; and

a Fabry-Perot etalon having an optical input in optical communication with said optical circulator etalon port,

wherein said FM optical signal from said optical circulator etalon port is at least partially reflected from said Fabry-Perot etalon back into said optical circulator etalon port and out from said optical circulator output.

3. The communication system of claim 1 further comprising a FM optical signal source generating said optical signal.

4. The transmitter of claim 3 wherein said FM optical signal source comprises a distributed feedback laser.

5. The transmitter of claim 1 wherein said first optical filter comprises a Fabry-Perot filter.

6. The transmitter of claim 1 wherein said first optical filter comprises a fiber grating filter.

7. The communication system of claim 1, wherein said first and second optical filters each have a bandwidth sufficient to transmit a carrier and a sideband of said optical signal.

8. The second photodetector of claim 1 further comprising an electrical input in communication with the electrical output of the first photodetector.

9. A method of transmitting an optical signal comprising the steps of:

providing a FM optical signal having a carrier and two sidebands;

optically filtering said FM optical signal to produce a first single sideband FM optical signal with the upper sideband removed;

optically filtering said FM optical signal to produce a second single sideband FM optical signal with the lower sideband removed; and

combining the first single sideband signal and the second single sideband signal, thereby reducing relative intensity noise in said FM optical signal.

10. A communication system comprising:

a FM optical signal source producing a FM optical signal at an optical output;

a beam splitter having an optical input in optical communication with said optical output of said FM optical signal source and having a first beam output and a second beam output;

a first optical filter having an optical input in optical communication with said first beam output and having an optical output,

wherein said first optical filter produces a first single sideband FM optical signal in response to said FM optical signal;

a second optical filter having an optical input in optical communication with said second beam output and having an optical output,

wherein said second optical filter produces a second single sideband FM optical signal in response to said FM optical signal;

a first photodetector having an optical input in optical communication with said first filter optical output and having an electrical output,

wherein said first photodetector produces a first detected electrical signal in response to said first single sideband FM optical signal;

a second photodetector having an optical input in optical communication with said second filter optical output and having an electrical output,

wherein said second photodetector produces a second detected electrical signal in response to said second single sideband FM optical signal; and

a differentiator having an electrical input in electrical communication with said first and second photodetector electrical outputs,

wherein said differentiator produces a demodulated electrical signal in response to said first and second detected electrical signals.

11. The communication system of claim 10 wherein said FM optical signal source comprises a distributed feedback laser.

12. A method of communication comprising the steps of:

providing a FM optical signal having a lower sideband, an upper sideband and a carrier;

splitting said FM optical signal to produce a first signal beam and a second signal beam;

optically filtering said first signal beam to remove said lower sideband to produce a first filtered beam;

optically filtering said second signal beam to remove said upper sideband to produce a second filtered beam;

detecting said first filtered beam to produce a first detected signal;

detecting said second filtered beam to produce a second detected signal;

combining said first and second detected signals to produce a combined signal; and

differentiating said combined signal to produce a demodulated signal.

13. A transmitter for an optical communication system comprising:

a FM optical signal source producing a FM optical signal at an optical output;

a beam splitter having an optical input in optical communication with said optical output of said FM optical signal source and having a first beam output and a second beam output;

a first optical filter having an optical input in optical communication with said first beam output,

wherein said first optical filter removes one sideband of said FM optical signal to produce a first single sideband FM optical signal; and

a second optical filter having an optical input in optical communication with said second beam output,

wherein said second optical filter removes one sideband of said FM optical signal to produce a second single sideband FM optical signal.

14. The transmitter of claim 13 wherein said FM optical signal source comprises a distributed feedback laser.

15. A method of transmitting an optical signal comprising the steps of:

providing a FM optical signal having a lower sideband, an upper sideband and a carrier;

splitting said FM optical signal to produce a first signal beam and a second signal beam;

optically filtering said first signal beam to remove said lower sideband to produce a first filtered beam; and

optically filtering said second signal beam to remove said upper sideband to produce a second filtered beam.

16. A receiver for an optical communication system comprising:

a beam splitter having an optical input, a first beam output and a second beam output;

a first optical filter having an optical output in optical communication with said first beam output and having an optical output,

wherein said first optical filter produces a first single sideband FM optical signal in response to a FM optical signal received at said beam splitter optical input;



a second optical filter having an optical output in optical communication with said second beam output and having an optical output,

wherein said second optical filter produces a second single sideband FM optical signal in response to said FM optical signal;

a first photodetector having an optical input in optical communication with said first filter optical output and having an electrical output,

wherein said first photodetector produces a first detected electrical signal in response to said first single sideband FM optical signal;

a second photodetector having an optical input in optical communication with said second filter optical output and having an electrical output,

wherein said second photodetector produces a second detected electrical signal in response to said second single sideband FM optical signal; and

a differentiator having an electrical input in electrical communication with said first and second photodetector electrical outputs,

wherein said differentiator produces a demodulated electrical signal in response to said first and second detected electrical signals.

17. A method of receiving an optical signal comprising the steps of:

splitting a FM optical signal having a lower sideband, an upper sideband and a carrier to produce a first signal beam and a second signal beam;

optically filtering said first signal beam to remove said lower sideband to produce a first single sideband FM optical signal;

optically filtering said second signal beam to remove said upper sideband to produce a second single sideband FM optical signal;

detecting said first single sideband FM optical signal to produce a first detected electrical signal;

detecting said second single sideband FM optical signal to produce a second detected electrical signal;

combining said first and second detected electrical signals to produce a combined electrical signal; and

differentiating said combined electrical signal to produce a demodulated signal.

* * * * *

US006356680B1

(12) United States Patent
Kirk et al.

(10) Patent No.: US 6,356,680 B1
(45) Date of Patent: Mar. 12, 2002

(54) METHOD AND SYSTEM FOR REMOVAL OF LOW ORDER OPTICAL TRANSMISSION MODES TO IMPROVE MODAL BANDWIDTH IN A MULTIMODE OPTICAL FIBER COMPUTER NETWORK

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(73) Assignee: **Enterasys Networks, Inc.**, Rochester, NH (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/650,622**

(22) Filed: **Aug. 30, 2000**

**Related U.S. Application Data**

(63) Continuation of application No. 09/082,767, filed on May 21, 1998, now Pat. No. 6,154,589.

(51) **Int. Cl.**$^{7}$ .................................................. **G02B 6/26**

(52) **U.S. Cl.** ............................ **385/29**; 385/27; 385/28; 385/38; 385/39; 385/123; 385/42

(58) **Field of Search** ............................ 385/15, 27, 28, 385/29, 31, 38, 39, 123, 88, 42

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| 6,154,589 A * | 11/2000 | Kirk et al. | 385/29 |

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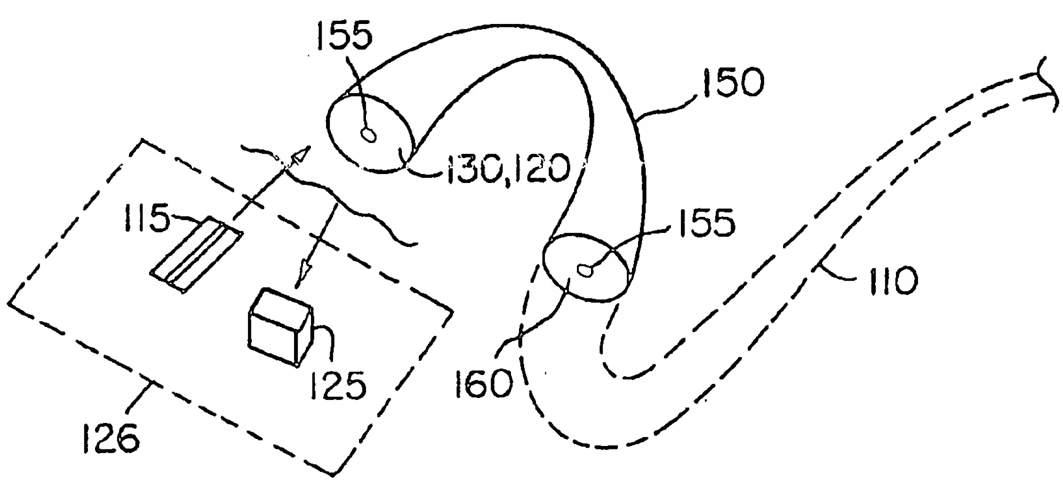
*Primary Examiner*—Brian Healy
(74) *Attorney, Agent, or Firm*—Wolf, Greenfield & Sacks, P.C.

(57) **ABSTRACT**

A method of improving modal bandwidth in computer networks using multimode optical fiber and single mode sources is disclosed in which the optical signal from a center of the optical fiber is prevented from reaching the detector. This is accomplished according to a number of different techniques including the use of opaque spots on the fiber media/fiber couplers or the use of dark-cored fiber couplers. These configurations prevent pulse splitting that occurs in single mode source/multimode fiber systems by preventing light from the multimode fiber's center from interfering with the detector. When this is achieved, the detector is insulated from the effects of pulse splitting, supporting increased data rates by increasing the modal bandwidth.

**18 Claims, 4 Drawing Sheets**



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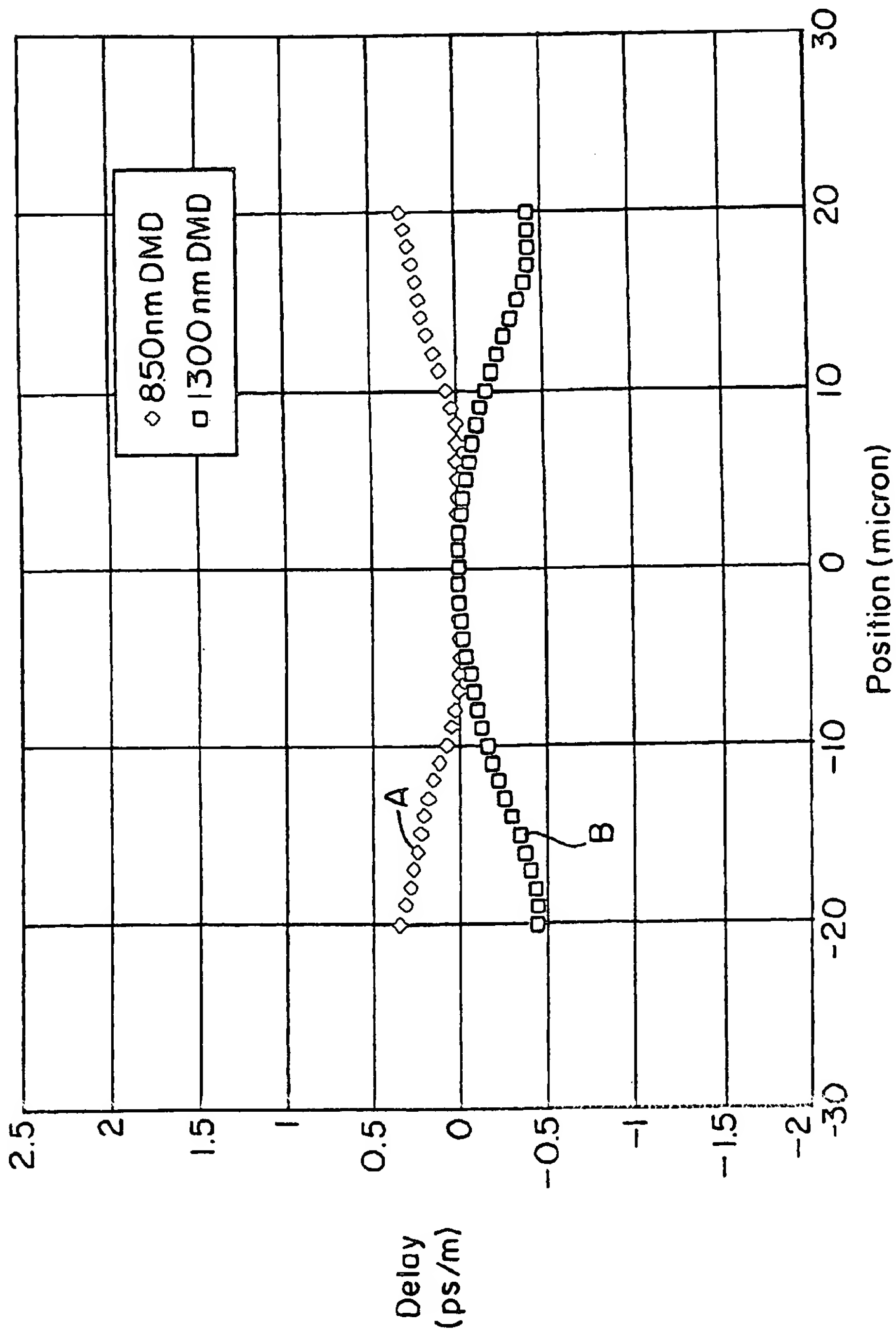
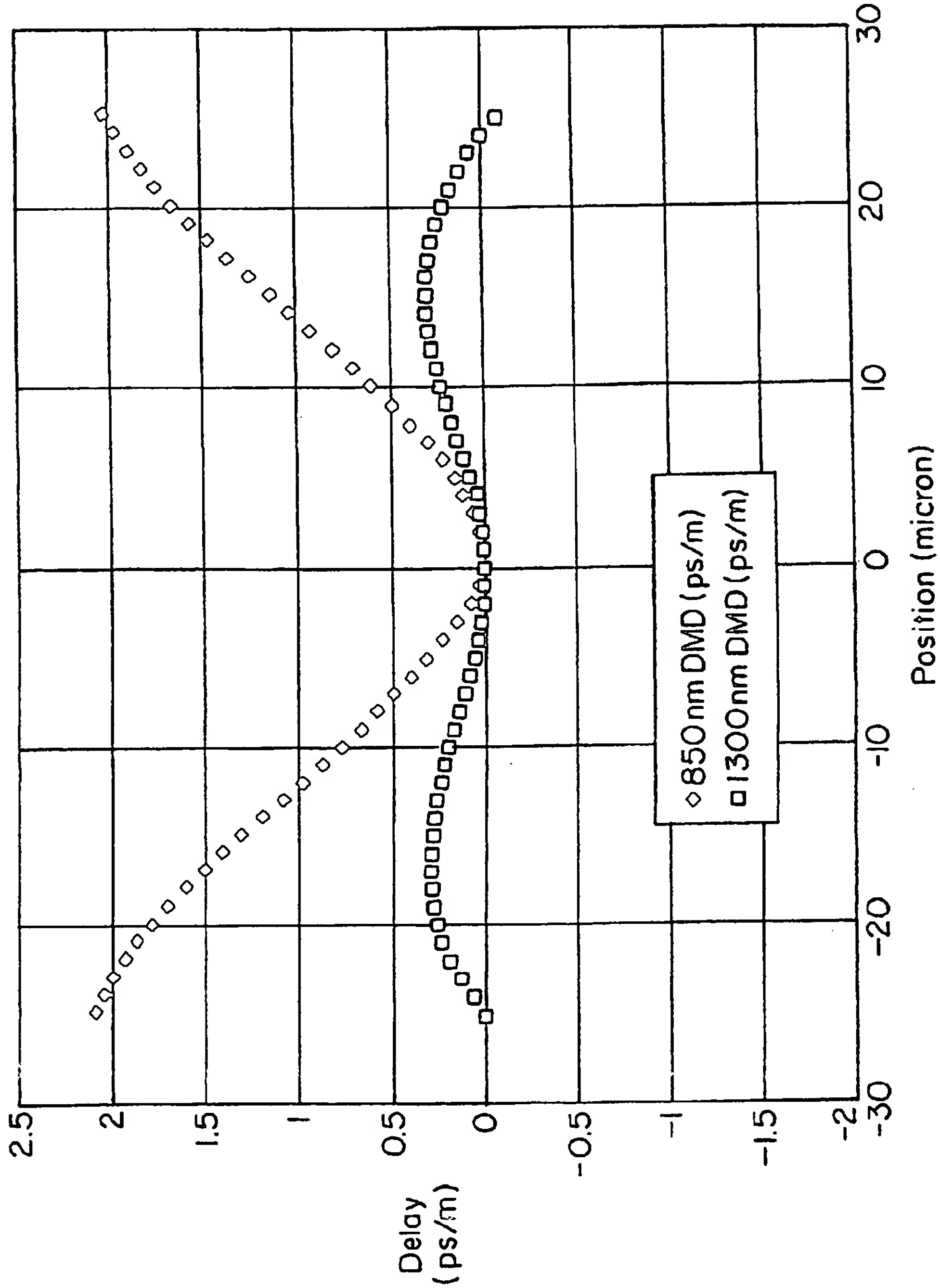

◇ 850nm DMD
□ 1300 nm DMD
A
B
Delay (ps/m)
Position (micron)
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-30
-20
-10
0
10
20
30

FIG. 1



Delay (ps/m)
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-30
-20
-10
0
10
20
30
Position (micron)
◇850nm DMD (ps/m)
□1300nm DMD (ps/m)


FIG. 2

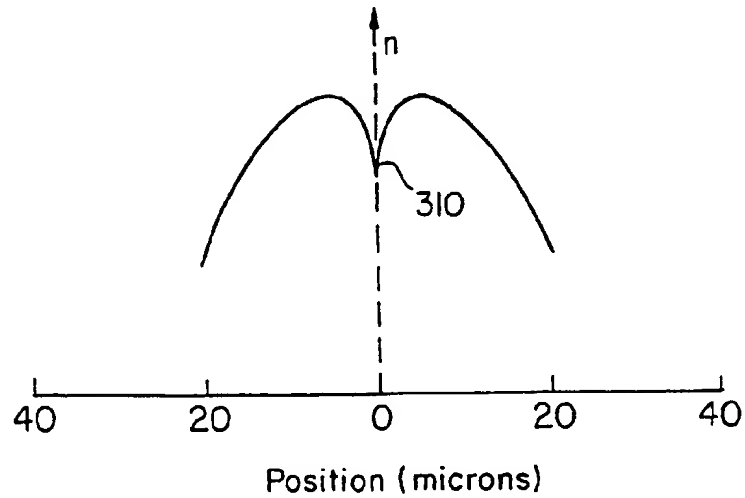

n
310
40
20
0
20
40
Position (microns)

FIG. 3

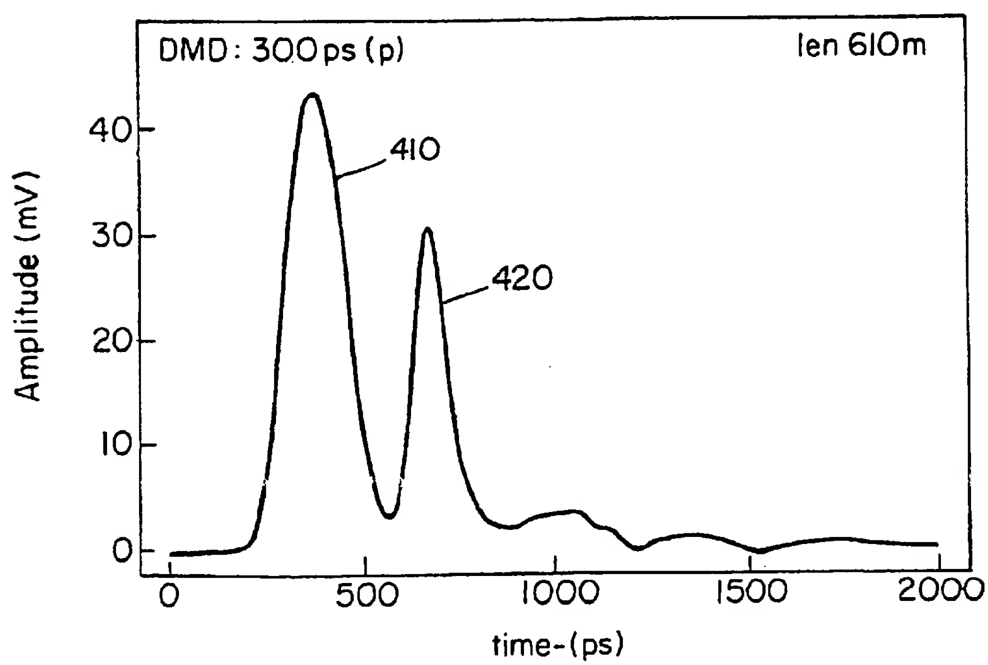

DMD: 30.0 ps (p)
len 610m
410
420
Amplitude (mV)
40
30
20
10
0
0
500
1000
1500
2000
time-(ps)

FIG. 4

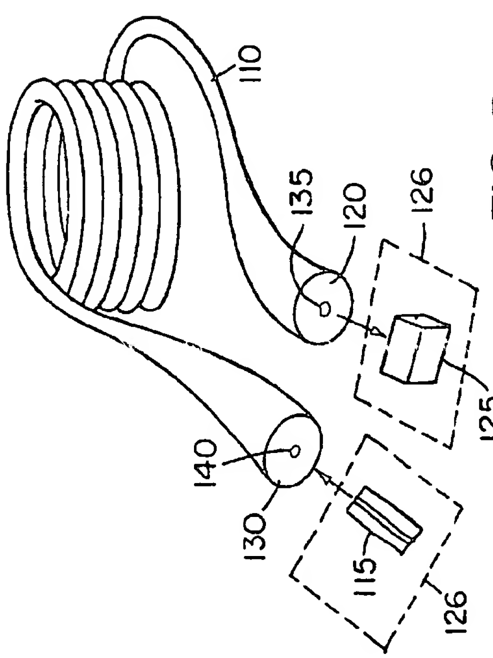



FIG. 5

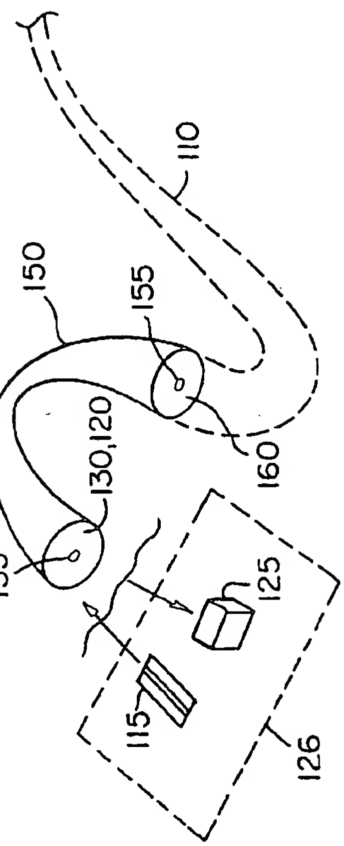



FIG. 6

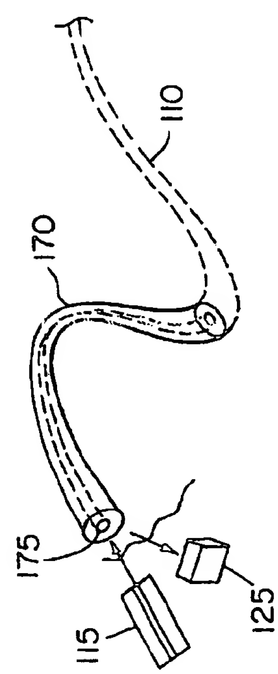



FIG. 7

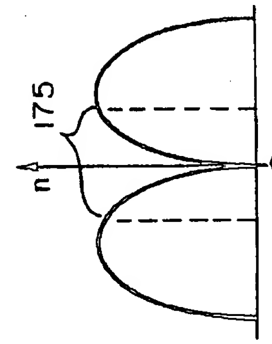



FIG. 8A

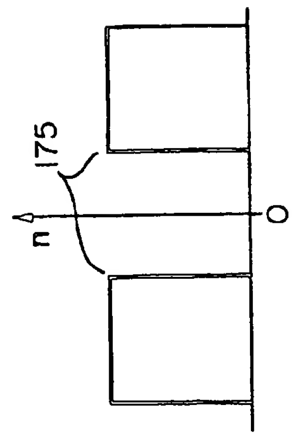



FIG. 8B

# METHOD AND SYSTEM FOR REMOVAL OF LOW ORDER OPTICAL TRANSMISSION MODES TO IMPROVE MODAL BANDWIDTH IN A MULTIMODE OPTICAL FIBER COMPUTER NETWORK

This application is a continuation of U.S. patent application Ser. No. 09/082,767 filed on May 21, 1998, and now U.S. Pat. No. 6,154,589.

## BACKGROUND OF THE INVENTION

Historically, local area computer networks (LANs) using optical data links have relied on light emitting diode (LED) sources launching into multimode optical fibers. The EIA/TIA and IEC Building Wiring Standards (TIA 568A) specify the use of 62.5/125 micron multimode optical fiber for intra-building wiring. These standards have resulted in the large-scale deployment of multimode optical fiber in existing computer networks.

In prior communication application technologies, these data transmission platforms have provided adequate bandwidth. Asynchronous transfer mode (ATM) computer networks can support data transmission rates as high as 622 megabits/sec (MBPS), but LED rise times, the chromatic dispersion associated with the relatively wide bandwidth of light produced by the LEDs, and multiple fiber transmission modes impose an upper cap on the potential data rates. Thus, LED/multimode fiber systems are generally limited to sub-gigabit/second (GBPS) data rates.

Newer computer applications requiring higher bandwidths and the increasing number of users that must be serviced by individual networks have led the push to provide GBPS performance, and better. In order to attain this performance in the context of existing optical data links, the LED light sources have been replaced with single mode sources such as vertical cavity surface emitting lasers (VCSEL) and Fabry-Perot lasers. These devices can produce the necessary rise times and have the narrow spectral widths required for GBPS data transmission speeds.

Computer network links modified to use single mode laser sources, however, many times still fail to achieve the data/error rates at GBPS data rates that would be predicted solely from the laser source performance. The problem has been traced to computer links using multimode optical fiber. In many instances, a pulse-splitting phenomena is detected, which increases the bit error rates to unacceptably high levels at these speeds.

The obvious solution to this problem is to use single mode fiber with the single mode sources. While being viable for newly installed computer networks, such a solution is impractical for the installed base of multimode fiber networks since running new fibers in and between buildings represents a significant expense.

Other solutions have been proposed to constrain pulse splitting in signals from single mode sources that have been launched into multimode fibers. In one case, the signal from the single mode source is launched into a short-length pigtail of single mode fiber. The other end of this fiber is then coupled to the existing multimode fiber, offset from the multimode fiber core center.

The problem with the offset single mode-multimode fiber coupling solution is the difficulty of implementing it in the typical computer network environment. The single mode fiber must be precisely misaligned to the multimode fiber such that the light is still launched into the multimode fiber with acceptable efficiency, and this misalignment must be maintained in the coupling module across its lifetime.

## SUMMARY OF THE INVENTION

According to the present invention, pulse splitting is constrained in single mode source/multimode fiber systems by preventing light from the center of the multimode fiber from being transmitted to the detector. When this is achieved, the detector is insulated from the effects of any pulse splitting, supporting data rates of greater than one GBPS by increasing the modal bandwidth.

In general, according to one aspect, the present invention features a method for improving modal bandwidth in an optical link, such as in a computer optical network, using a multimode optical fiber. The method comprises generating an optical signal with a single mode laser source and coupling the optical signal into the multimode optical fiber. The optical signal from a center portion of the optical fiber, however, is blocked from reaching a detector of the optical signal.

In one implementation, the source is a Fabry-Perot or vertical cavity surface emitting laser.

In specific embodiments, an opaque spot is inserted between the laser source and the detector to block the center of the optical fiber from transmitting a detectable optical signal. As such, the spot is applied to a fiber coupler or the fiber of the network. Further, the spot may be applied to either the entrance or exit apertures of the fiber. In any case, the spot should be approximately 4 to 7 microns in diameter.

Alternatively, a fiber coupler with a dark central core is also useful. It can be inserted either at the detector or laser source end of the optical fiber, or both.

According to another aspect, the invention features multimode optical fiber of the computer network with at least one opaque spot for blocking the optical signal from a center portion of the optical fiber from reaching the detector.

Finally, according to another aspect, the invention also features a fiber coupler with a dark core for blocking the optical signal from a center portion of an installed multimode optical fiber from reaching a detector.

The above and other features of the present invention, including various novel details of construction and combinations of parts, and other advantages, will now be more particularly described with reference to the accompanying drawings and pointed out in the claims. It will be understood that the particular method and device embodying the invention are shown by way of illustration and not as a limitation of the invention. The principles and features of this invention may be employed in various and numerous embodiments without departing from the scope of the invention.

## BRIEF DESCRIPTION OF THE DRAWINGS

In the accompanying drawings, like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention.

FIGS. 1 and 2 are plots of the differential mode delay in picoseconds per meter as a function of axial launch position for 850 nanometer and 1300 nanometer sources in two exemplary multimode fiber samples;

FIG. 3 is a plot of the index of refraction (n) as a function of axial position for an exemplary multimode fiber;

FIG. 4 shows a pulse function input signal from a 1300 nm single mode Fabry-Perot laser launched into a 610 meter long, 62.5 micron, fiber run (horizontal scale is 500 ps/division, and the vertical scale is 10 milliVolts/division);

FIG. 5 is a schematic drawing showing embodiments of the inventive system for increasing modal bandwidth by preventing center mode light from reaching the detector;

FIG. 6 is a schematic drawing showing other embodiments of the invention using a fiber coupler;

FIG. 7 is a schematic drawing showing still other embodiments of the invention using a dark core fiber coupler; and

FIGS. 8A and 8B are two refractive index profiles for the dark core fiber.

## DETAILED DESCRIPTION OF THE INVENTION

The modal bandwidth of graded index multimode optical fiber depends directly on the fiber's refractive index profile. The profile is designed to compensate for the different paths traveled by the numerous optical modes supported by the multimode optical fiber. The goal is to equalize delays of all propagating modes. The propagation time of an optical mode through a fiber is proportional to the optical path length. Low order modes propagate nearly straight through the fiber, traveling a distance close to the fiber's physical length L. Higher order modes travel at higher angles, and the physical distance L traveled is consequently longer. The optical path length of all modes is a product of the distance traveled and the refractive index of the optical medium along their respective paths. Compensation for the different modal physical distances is achieved by lowering the refractive index of the region of the fiber in which the higher order modes travel.

The index of refraction compensation is performed during the manufacture of the fiber. When the index is graded correctly, modes of different orders will propagate at compensated velocities and arrive at the far end of the fiber at nearly the same time. Research has shown that the optimum grading is obtained with a refractive index profile of the form:

$$n(r)=n1*[1-2\Delta n[1-(r/a)^g]]^{0.5} \text{ for } r<a,$$

and

$$n(r)=n2 \text{ for } r>=a,$$

where:

n(r) is the refractive index at radial position r,

n1 is the refractive index peak value,

n2 is the refractive index of the cladding glass,

a is the core diameter,

$\Delta n$ is the index difference$=(n1^2-n2^2)/(2*n1^2)$, and

g is the profile parameter, a value of g=1 gives a straight line curve from 0 to a, a value of g=∞ gives a flat, or step index profile.

A g value of approximately 1.9 to 2.0 has been found to provide optimal propagation delays for multimode optical fibers.

Differential mode delay (DMD) measurements are a method for testing the effectiveness of the index profiling. A fiber is tested by launching a single mode pulse into the core at the core/cladding boundary. The output of the fiber is detected with a high bandwidth detector. The input point is then traversed across a diameter of the fiber while the relative time difference is read and recorded at the other end. The relative delays are plotted against radial position. Fibers with lower DMD profiles, or differences between the delays experienced at the fiber's center relative to near the core/cladding interface, have higher modal bandwidths than those with high DMD profiles.

FIG. 1 is a plot of the DMD for a graded index multimode fiber. Curves A and B show a relatively acceptable DMD for a multimode fiber operating at **850** (see ◇ data points) and **1300** (see □ data points) nanometers (nm), respectively. In each case, the DMD is less than 0.5 picoseconds per meter (ps/m).

FIG. 2 is a plot of the DMD for another multimode, nominally similar, fiber. The DMD is limited for 1300 nm, but at 850 nm the DMD reaches 2 ps/m for modes launched at a fiber axial position of+/-25 microns from the fiber's center. As a result, when operating at 850 nm, modes transmitted along the fiber's center travel much faster than those near the cladding/core interface.

The reduced delay for modes traveling along the fiber's center is theorized to be an artifact of the manufacturing techniques used for the multimode fiber. The fibers are manufactured by slowly depositing closely controlled combinations of chemicals on the inner surface of a hollow glass tube. This process slowly closes the tube off, slowly reducing its inner diameter by the sequential depositions. The last stages, just before the tube is closed-off, can sometimes be incomplete, yielding indexes such as that illustrated in FIG. **3** when the tube is pulled into the fiber. A sharp anomaly **310** in the graded index (n) occurs near the fiber's center, position **0**.

It is theorized that the fiber's center index of refraction anomaly results in pulse splitting such as that shown in FIG. **4** when a single mode laser launches into a multimode fiber. In an experiment, a 1300 nm single mode Fabry-Perot laser launched a pulse function into a 610 meter long, 62.5 micron, fiber run. In the plot, the horizontal scale is 500 ps/division, and the vertical scale is 20 milliVolts/division.

After propagating the 610 meters, the original signal is converted into an initial pulse 410 and a secondary pulse 420. This pulse splitting differs from the pulse broadening usually seen when multimode sources are launched into multimode fibers.

The highly multimodal and wide bandwidth characteristics of the LED are believed to excite all or most of the fiber's transmission modes. As a result, a relatively small amount of the energy carried by the fiber is transmitted in the fiber's center and thus experiences the problematic transmission delay associated with the center index anomalies. In contrast, it is believed that the single mode laser source excites relatively few of the fiber's modes. Some of those modes propagate along the fiber's center, experiencing little delay, and an almost equivalent optical power is contained in other modes that propagate more toward the cladding/core interface, experiencing delay that would be predicted from the graded fiber configuration. These effects result in the distinct splitting, which severely undermines the decision logic in the detector yielding unacceptably high error rates when the transmission speeds approach 1 GBPS. While not all existing multimode fiber has this problem, a non-trivial amount does, and there is no easy test for identifying the problem fibers.

FIG. **5** illustrates one embodiment of a system for preventing the pulse splitting in multimode fiber **110**/single mode source **115** computer data network transmission systems. Briefly, the invention is based on the principle that an opaque spot, applied to the center axis of the multimode fiber, between the detector and source, prevents the fiber modes traveling along the fiber's center axis from reaching the detector. Experiments have shown that stopping the coupling of the fiber's center modes to the detector prevents either the pulse splitting effect entirely or the effect at the detector where it causes problems.

In the embodiment of FIG. 5, an opaque spot **135** is applied to exit aperture **120** of the fiber **110**, which forms the optical transmission media of the network. This configuration prevents any center modes of the optical signal propagating in the multimode fiber **110** from reaching the detector **125**, which is typically part of a network interface card **126** of the computer node or network communications device. As a result, the center modes, which may propagate too quickly due to a reduced center index of refraction present in some multimode fibers, will not contribute to a pulse splitting effect at the detector **125** thereby preserving modal bandwidth.

The opaque spot **135** is preferably large enough to prevent substantially all of the energy in the center modes from reaching the detector **125**. In the preferred embodiment, the opaque spot blocks approximately 90% of the energy. This requires a spot approximately 5 to 7 microns in diameter for 62.5 micron fiber. The opaque spot is preferably circular and applied substantially centered on the fiber's axis, as shown.

The opaque spot **135** is applied according to a number of different techniques. In the preferred embodiment, it is painted-on, possibly using a jig. Alternatively, it is scribed, etched, or deposited on the fiber end.

As also shown in FIG. 5, an opaque spot **140** is alternatively applied to the input or entrance aperture **130** of the fiber **110**. This second configuration prevents the optical signal from the single mode laser source **115**, typically also found in a network interface card **126**, from exciting any of the center modes of the fiber **110**. A characteristic of multimode fibers that allows this embodiment to work is the limited coupling between the fiber's modes. That is, the center modes will not be excited by optical power crossing over from other modes.

According to the invention, the opaque spot is applied to the fiber's input aperture **130** or output aperture **120**, individually. Alternatively, opaque spots **140, 135** are applied to both of the input and output apertures **130, 120**.

FIG. **6** shows another embodiment in which the opaque spot(s) is/are not necessarily applied to the existing multimode fiber **110** but applied to a fiber pigtail or coupler **150** between the existing multimode fiber **110** and the single mode light source **115** and/or detector **125**. As before, the fiber couplers **150** are used at the detector or laser ends, or both. Moreover, the opaque spots **155** on the coupler **150** can be applied to the entrance/exit aperture ends **130, 120** that face the laser **115**/detector **125** or to the coupler end **160** that interfaces with the multimode fiber **110**, or both.

FIG. **7** shows still another embodiment of the invention. In this case, a coupler **170** is used as in the embodiment in FIG. **6**. The fiber coupler's refractive index, however, is constructed so that it has a dark core **175** that can not transmit light, rather than the reliance on the opaque spots.

FIGS. **8**A and **8**B show two index profiles that will not transmit any light through the fiber's center axis. By doping the fiber during its manufacture such that the index of refraction drops sharply near the fiber's center axis, as shown in FIG. **8**A, light will be coupled only into modes existing in an annular ring centered on the fiber. Similarly, FIG. **8**B shows a fiber index with an annular step profile. Here, the center 5–7 microns of the fiber transmits no light. As in the previous embodiments, these dark core couplers **170** are placed either at the front end between the transmission fiber **110** and the laser **115** at the tail end between the transmission fiber **110** and the detector **125**, or both.

While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. Those skilled in the art will recognize or be able to ascertain using no more than routine experimentation, many equivalents to the specific embodiments of the invention described specifically herein. Such equivalents are intended to be encompassed in the scope of the claims.

What is claimed is:

**1**. A method of improving modal bandwidth of a multimode optical fiber, comprising:

applying a blocking area to the multimode optical fiber such that substantially no optical signal exits from a center portion of the multimode optical fiber, wherein the blocking area comprises an opaque spot.

**2**. A method of improving modal bandwidth of a multimode optical fiber, comprising:

applying a blocking area to the multimode optical fiber such that substantially no optical signal exits from a center portion of the multimode optical fiber; and

generating the optical signal with one of:

a single-mode laser source;

a Fabry-Perot laser; and

a vertical cavity surface emitting laser.

**3**. The method as recited in claim **1**, wherein the blocking area is positioned over a center axis of the multimode optical fiber.

**4**. The method as recited in claim **1**, further comprising applying the blocking area to at least one of the exit aperture and an entrance aperture of the multimode optical fiber.

**5**. A method of improving modal bandwidth of a multimode optical fiber, comprising:

applying a blocking area to at least one of the exit aperture and an entrance aperture of the multimode optical fiber such that substantially no optical signal exits from a center portion of the multimode optical fiber;

wherein the blocking area is applied by at least one of:

painting;

scribing;

etching; and

depositing.

**6**. A method of improving modal bandwidth of a multimode optical fiber, comprising:

applying a blocking area to the multimode optical fiber such that substantially no optical signal exits from a center portion of the multimode optical fiber; wherein the blocking area is a spot having a diameter that is approximately 6.5% to 11.2% of a diameter of the multimode optical fiber.

**7**. A method of improving modal bandwidth of a multimode optical fiber, comprising:

applying a blocking area to the multimode optical fiber such that substantially no optical signal exits from a center portion of the multimode optical fiber; wherein the blocking area is of a construction sufficient to block at least 90% of the energy in the center modes of the multimode optical fiber.

**8**. An optical signal transmission system, comprising:

multimode optical fiber; and

a blocking area comprising an opaque spot applied to the multimode optical fiber such that substantially no optical signal exits from a center portion of the multimode optical fiber.

**9**. The system as recited in claims **8**, wherein the blocking area is positioned over a center axis of the multimode optical fiber.

10. The system as recited in claim 8, wherein the blocking area is applied to at least one of an exit aperture and an entrance aperture of the multimode optical fiber.

11. An optical signal transmission system, comprising:

multimode optical fiber; and

a blocking area applied to the multimode optical fiber such that substantially no optical signal exits from a center portion of the multimode optical fiber, wherein the blocking area is of a construction sufficient to block at least 90% of the energy in the center modes of the multimode optical fiber.

12. An optical signal transmission system, comprising:

multimode optical fiber; and

a blocking area applied to the multimode optical fiber such that substantially no optical signal exits from a center portion of the multimode optical fiber, wherein the opaque spot has a diameter that is approximately 6.4% to 11.2% of a diameter of the multimode optical fiber.

13. An optical signal transmission system, comprising:

multimode optical fiber; and

a blocking area applied to the multimode optical fiber such that substantially no optical signal exits from a center portion of the multimode optical fiber;

wherein the blocking area is applied by at least one of:

painting

scribing

etching; and

depositing.

14. An optical signal transmission system, comprising:

multimode optical fiber; and

a fiber coupler, coupled to the multimode optical fiber, to substantially prevent an optical signal from exiting a center portion of the multimode optical fiber,

wherein the fiber coupler comprises an opaque blocking spot applied to at least one of an exit aperture and an entrance aperture of the fiber coupler.

15. The system as recited in claim 14, wherein the fiber coupler transmits only an annular ring of light into the multimode optical fiber.

16. An optical signal transmission system, comprising:

multimode optical fiber; and

a fiber coupler, coupled to the multimode optical fiber, to substantially prevent an optical signal from exiting a center portion of the multimode optical fiber,

wherein the fiber coupler comprises a blocking area applied to at least one of an exit aperture and an entrance aperture of the fiber coupler, and the blocking area is of a construction sufficient to block at least 90% of the energy in the center modes of the multimode optical fiber.

17. An optical signal transmission system, comprising:

multimode optical fiber; and

a fiber coupler, coupled to the multimode optical fiber, to substantially prevent an optical signal from exiting a center portion of the multimode optical fiber,

wherein the fiber coupler comprises a blocking area applied to at least one of an exit aperture and an entrance aperture of the fiber coupler, and the fiber coupler further comprises optical fiber having a first end being the entrance aperture of the fiber coupler and a second end being the exit aperture of the fiber coupler, wherein the blocking area is applied to at least one of the entrance aperture and the exit apertures of the optical fiber of the fiber coupler.

18. The system as recited in claim 17, wherein the blocking area is applied by at least one of:

painting;

scribing;

etching; and

depositing.

* * * * *

US005359447A

# United States Patent [19]

**Hahn et al.**

[11] **Patent Number: 5,359,447**

[45] **Date of Patent: Oct. 25, 1994**

[54] **OPTICAL COMMUNICATION WITH VERTICAL-CAVITY SURFACE-EMITTING LASER OPERATING IN MULTIPLE TRANSVERSE MODES**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[21] Appl. No.: **83,739**

[22] Filed: **Jun. 25, 1993**

[51] **Int. Cl.**$^5$ .............................................. **H04B 10/00**

[52] **U.S. Cl.** ................................... **359/154**; 359/173; 372/38

[58] **Field of Search** ............... 359/154, 161, 173, 180, 359/188, 195; 372/38, 45


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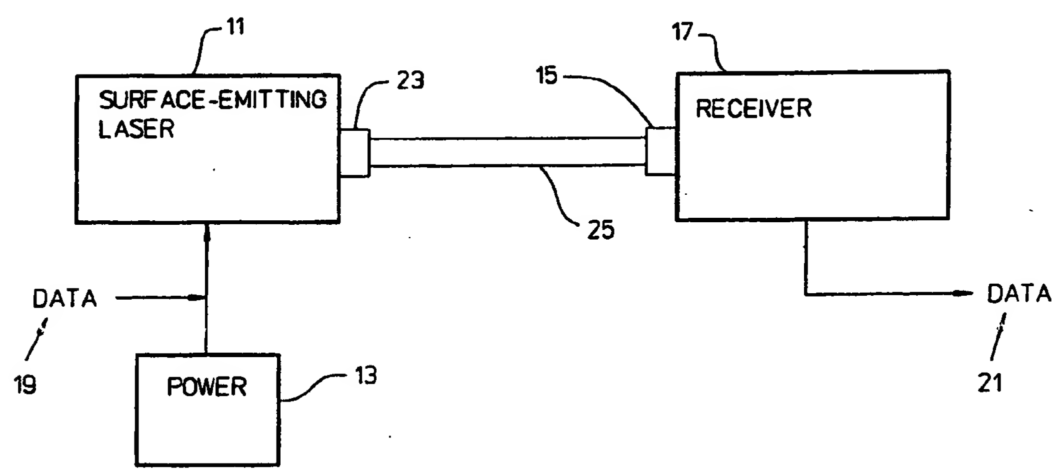
*Assistant Examiner*—Kinfe-Michael Negash

[57] **ABSTRACT**


An optical communication system using a relatively large-area vertical-cavity surface-emitting laser. The laser has an opening larger than about eight micrometers and is coupled to a multimode optical fiber. The laser is driven into multiple transverse mode operation, which includes multiple filamentation as well as operation in a single cavity.


**6 Claims, 2 Drawing Sheets**

Cl 16



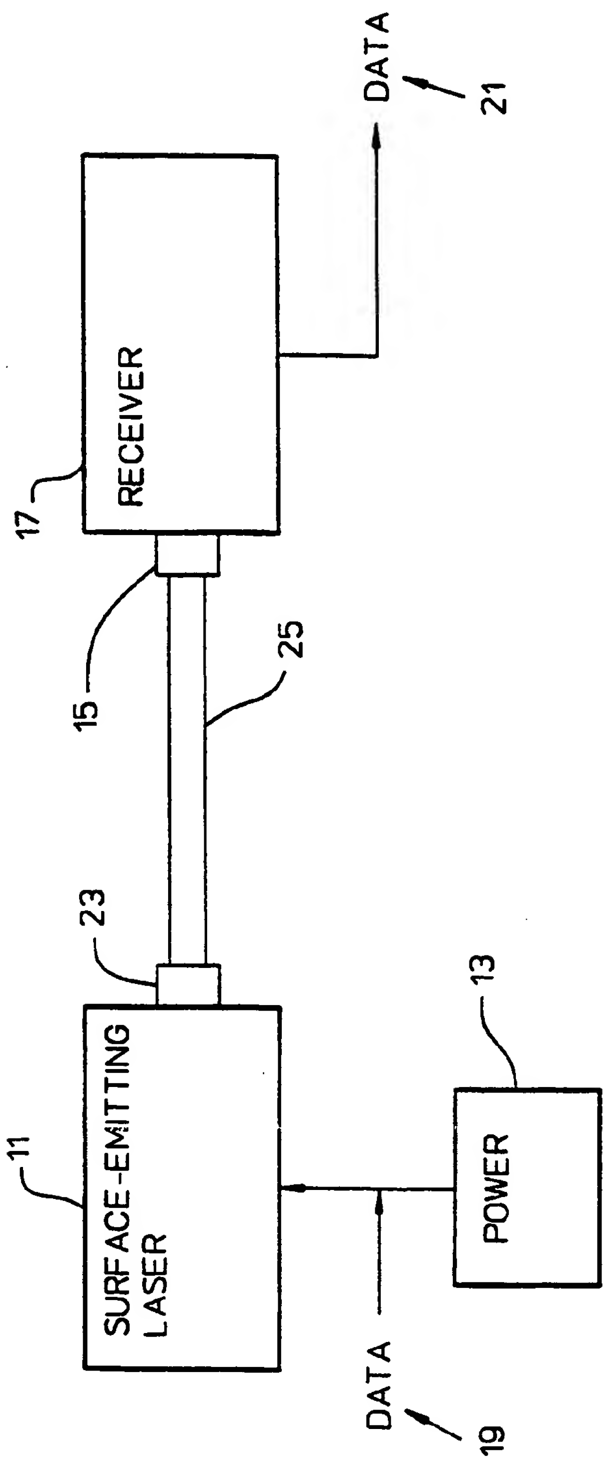

DATA
21
RECEIVER
17
15
25
23
13
SURFACE-EMITTING LASER
11
POWER
DATA
19

FIG. 1

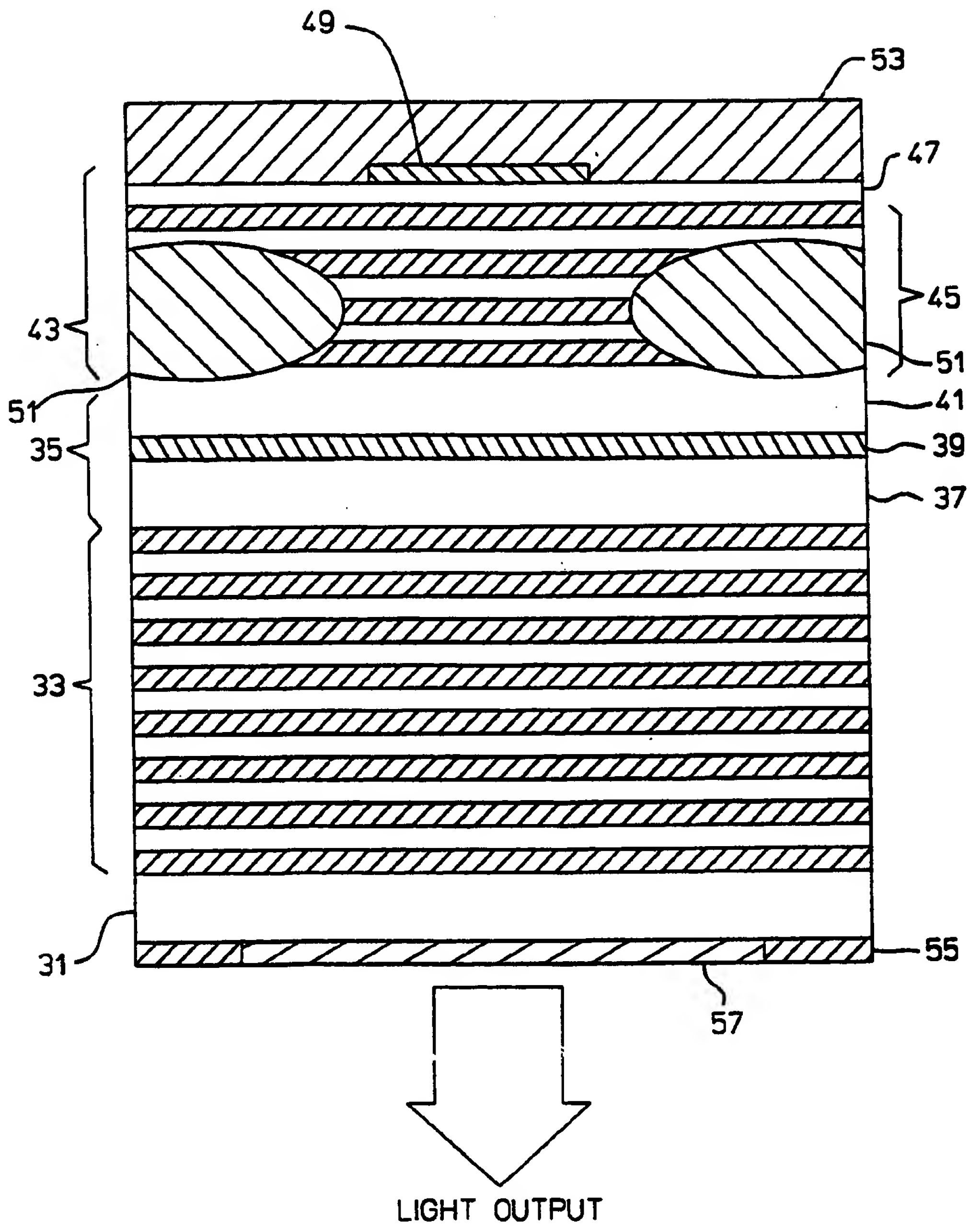



FIG. 2

# OPTICAL COMMUNICATION WITH VERTICAL-CAVITY SURFACE-EMITTING LASER OPERATING IN MULTIPLE TRANSVERSE MODES

## BACKGROUND OF THE INVENTION

The present invention relates generally to optical transmission of signals and more particularly to an optical communication network of the kind having a multimode optical fiber that receives a multiple mode beam of light from a vertical-cavity, surface-emitting laser being operated in multiple modes or multiple filamentation.

Optical communication systems are used to carry information from one location to another. One of the advantages of optical systems is that they have extremely wide bandwidths. This means that optical systems can carry much more information than can other kinds of communication systems such as radio or microwave. For example, nearly all long-distance telephone calls are carried by optical communication systems because a single optical fiber can carry thousands of conversations at the same time. Optical systems also offer the potential of carrying large quantities of digital data for high-speed computers more efficiently and economically than other communication systems.

Every optical communication system includes, at a minimum, three elements: a transmitter that generates a beam of light and modulates the beam with data to be transmitted, a receiver that receives the beam of light and recovers the data from it, and a medium such as an optical fiber that carries the beam of light from the transmitter to the receiver. Typically the transmitter uses a laser or a light-emitting diode ("LED") to generate the light beam. The receiver uses photodetectors or the like to receive the beam. The medium may be an optical waveguide or the like instead of an optical fiber.

Light may travel through an optical medium in single mode or multiple modes. In general, a "mode" of an electromagnetic wave can be defined as a stationary pattern of the wave. In the special case of a beam of light (which may be thought of as an electromagnetic wave in the optical portion of the spectrum), a mode is a wave pattern that does not change the shape of its transverse field distribution as it propagates through the medium.

A given optical medium may be capable of supporting many modes or only a single mode. This is determined by physical parameters such as—in the case of an optical fiber—the diameter of the fiber and the difference between the indices of refraction of the core and the cladding.

Likewise, many lasers can be caused to operate in single mode or in multiple modes. This can be done by a suitable choice of device structure and drive conditions. Multiple mode operation has generally been understood to consist of multiple modes in one laser cavity. However, studies have shown that multiple mode laser operation can occur with filamentation due to non-uniform gain or loss. This is especially true for lasers with large transverse dimensions compared with the wavelength. For convenience, the terms "multiple mode" and "multimode" as used herein to describe the operation of a laser will include both multiple modes in a single laser cavity and multiple filamentation.

Optical communication systems are subject to various kinds of losses and limitations. Among these are intermodal dispersion, chromatic dispersion and mode selective l sses. All of these have the effect of decreasing the signal-to-noise ratio, and therefore it is desirable to eliminate r minimize them as much as possible.

Intermodal dispersion becomes worse as the length of the fiber increases. Intermodal dispersion only affects multimode fibers, and therefore single mode fibers are preferred for communication over long distances. As used herein, a "long" distance means a distance that is more than a few hundred meters and a "short" distance is one that is less than a few hundred meters. Of course, it should be understood that this is an approximation; multimode fibers up to a few kilometers in length have been used successfully, but usually when the required length of the fiber exceeds a couple of hundred meters a single mode fiber will be used.

Chromatic dispersion also becomes more severe as the length of the fiber increases but, unlike intermodal dispersion, chromatic dispersion affects both single mode and multimode fibers. The adverse effects of chromatic dispersion can be minimized by using a highly coherent laser because such a laser produces a light beam of very narrow spectral width. Accordingly, highly coherent lasers have been preferred for most optical communication systems, especially for communication over long distances.

Of course, single mode optical fibers can also be used over short distances (less than a few hundred meters), for example to carry digital data from one computer to another in a local network or even to carry data between points less than a meter apart within a single computer. However, multimode optical fibers are preferred for short-distance optical communication systems because their relative ease of packaging and alignment makes them considerably less expensive than single mode fibers.

A drawback of multimode optical media has been that these media are subject to mode selective losses. A mode selective loss may be characterized as a physical condition that affects the optical characteristics of the medium. These losses may be, for example, splices in the medium, power splitters and other devices that are connected to the medium, and physical defects such as poor quality connections and misalignment of components. Although such physical conditions can be reduced by careful design and construction, in practice it is rarely possible to produce a system that is totally free of them. Therefore, all practically realizable multimode optical communication systems will be subject to at least some mode selective losses.

The actual mechanism by which physical discontinuities produce mode selective losses will now be briefly discussed. Interference between different modes in a multimode medium carrying a coherent light beam produces a speckle pattern. Ideally this speckle pattern would remain stationary, but in practice it moves about within the medium. Speckle pattern movement may be caused by physical jostling or other movement of the fiber itself (relatively slow movement) or by laser mode partitioning and the like (relatively fast movement). Movement of the speckle pattern in a system having mode selective losses results in power variations in the received signal. These variations are caused by the mode selective l sses and result in a degradation of the signal-to-noise ratio. In digital systems, a degradation of the signal-to-noise ratio manifests itself as an increased bit error rate.

Mode selective losses are described in more detail in such references as Epsworth, R. E., "The Phenomenon of Modal N ise in Analogue and Digital Optical Fibre Systems", *Proceedings of the 4th European Conference on Optical Communications*, Genoa, September, 1978, pp. 492–501, and in Kanada, T., "Evaluation of Modal Noise in Multimode Fiber-Optic Systems", *IEEE Journal of Lightwave Technology*, 1984, LT-2, pp. 11–18.

Mode selective losses can be avoided by using a relatively low-coherence light source such as an LED or a self-pulsating laser diode ("SPLD") rather than a highly coherent laser. The use of LEDs in optical communication systems is described in Soderstrom, R., et al., "Low Cost High Performance Components of Computer Optical Data Links", *Proceedings of the IEEE Laser and Electrooptics Society Meeting*, Orlando, Fla. 1989. A disadvantage of using LEDs in optical communication systems is that the coupling efficiency between an LED and an optical fiber is very low. In addition, LEDs are inherently slow, which limits the maximum data rate.

SPLDs have been used in such systems as the Hewlett-Packard HOLC-0266 Mbaud Fiber Channel multimode fiber data link, manufactured by the assignee hereof; this is described in Bates, R. J. S., "Multimode Waveguide Computer Data Links with Self-Pulsating Laser Diodes", *Proceedings of the International Topical Meeting on Optical Computing*, Kobe, Japan, April, 1990, pp. 89–90. The coupling efficiency between an SPLD and an optical fiber is better than that between an LED and an optical fiber, but still is not optimal. In addition, the maximum data rate that can be achieved with an SPLD is limited. Neither SPLD nor LED systems have been able to achieve reliable data rates as high as 1 gigabit per second

From the foregoing it will be apparent that there remains a need for a reliable and economical way to carry data at rates exceeding one gigabit per second by means of optical communication systems operating over short distances.

## SUMMARY OF THE INVENTION

The present invention provides an optical communication system that can transmit data reliably and economically by means of multimode optical media at any rate up to and exceeding one gigabit per second.

Briefly and in general terms, the invention is embodied in an optical communication system having a vertical-cavity, surface-emitting laser ("SEL"). A multimode optical medium such as an optical fiber is coupled to the SEL. A power supply provides a bias current that drives the SEL into multiple transverse mode operation, preferably in more than two distinct modes. The SEL generates a beam of light that has a lower coherence than that provided by a single-mode laser. This beam of light is modulated with data carried by an incoming signal. The SEL preferably has an aperture larger than about eight micrometers ("$\mu$m") through which the modulated light beam is emitted.

The optical medium carries the modulated beam of light from the SEL to a receiver at a remote location. The receiver, which may be closer than a meter or farther away than 100 meters, recovers the data from the light beam.

Other aspects and advantages of the invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, illustrating by way of example the principles of the invention.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic diagram of a preferred embodiment of an ptical communication system according to the invention; and

FIG. 2 is a cross-sectional view of a vertical-cavity, surface-emitting laser of the kind used in the communication system shown in FIG. 1.

## DESCRIPTION OF THE PREFERRED EMBODIMENT

As shown in the drawings for purposes of illustration, the invention is embodied in a novel optical communication system having a vertical-cavity, surface-emitting laser ("SEL") driven into multiple transverse mode operation to provide a light beam that carries data reliably and efficiently over a multimode optical medium. To avoid the expense of single mode fibers for communicating over distances of less than a few hundred meters, existing optical communication systems have used multimode fibers, but such systems have been subject to unacceptably high mode selection losses or have used low-coherence light sources such as LEDs and SPLDs that have not been able to achieve sufficiently high data rates.

A communication system according to the invention uses an SEL operating in multiple transverse modes. The SEL provides a beam of light that has lower coherence than the highly-coherent light beams typically used in single mode systems but higher coherence than the low-coherence beams provided by LEDs and self-pulsating lasers. A multimode optical medium carries the beam from the SEL to a receiver which may be less than a meter away or 100 meters or more distant. The system can transmit data at any rate up to and exceeding 1.5 gigabits per second with a negligible bit error rate. The system provides all the benefits, such as easy alignment, simple packaging and low cost, usually associated with multimode optical media.

A preferred embodiment of the invention will now be discussed in more detail. As shown in FIG. 1, the invention is embodied in an optical communication network that includes an SEL **11**, a power supply **13** that provides a bias current to drive the SEL into multiple transverse mode operation, and a multimode optical medium **15** optically coupled to the SEL to carry the optical signal from the SEL to a remotely-located receiver **17**. The SEL is responsive to a signal carrying data (designated generally as **19**) to provide an optical signal modulated with the data. The receiver **17**, which is optically coupled to the optical medium **15**, receives the modulated optical signal and recovers the data (designated generally as **21**) therefrom.

Various kinds of multimode optical media such as optical fibers and waveguides may be used for the medium **15**. The SEL **11** and the receiver **17** are coupled to the medium **15** through suitable couplings **23** and **25**. As will be discussed in more detail presently, the SEL **11** is preferably driven in more than two distinct transverse modes; as noted previously, this may comprise multiple filamentation.

A preferred method of fabricating the SEL **11** is illustrated in FIG. 2. The SEL is grown on an n+GaAs (gallium arsenide) substrate **31**. A bottom output mirror, for example 18.5 pairs of n-doped GaAs/AlAs (gallium arsenide/aluminum arsenide) quarter-wave layers (generally designated **33** in the drawing), is epitaxially grown on the substrate **31**. The interface between the

layers is graded using an AlAs/GaAs/Al(0.3)Ga(0.7)As variable duty cycle short period superlattice ("SPSL"). The SPSL reduces any heterojunction band discontinuities at the GaAs/AlAs interface. The doping level is $1\times10^{18}cm^{-3}$ in uniform regions and $3\times10^{18}cm^{-3}$ in graded regions. For simplicity only a few of the 18.5 pairs of layers are shown in the figure. The reflectivity of the bottom mirror 33 is 98.9%.

Next an optical cavity structure 35 is grown. The cavity structure includes an n-cladding layer 37, a quantum well 39, and a p-cladding layer 41. The cladding layers 37 and 41 comprise Al(0.3)Ga(0.7)As doped to $1\times10^{18}cm^{-3}$, reduced to $5\times10^{17}cm^{-3}$ adjacent the quantum well 39. The quantum well 39 comprises 3 MQW of strained In(0.2)Ga(0.8)As (indium gallium arsenide) having a thickness of about 80 Å (Å=Angstrom), with GaAs barriers having a thickness of 100 Å.

Above the quantum well 35 is a highly-reflective top mirror 43. The reflectivity of the top mirror is greater than 99.96%. The top mirror 43 comprises, for example, 15 pairs of GaAs/AlAs quarter wave layers (generally designated 45), a phase matching layer 47, and an Au (gold) layer 49. A proton isolation region 51 surrounds the perimeter of the quarter wave layers 45. As with the bottom mirror 33, only a few of the quarter wave layers 45 are actually shown in FIG. 2. The interfaces between the quarter wave layers are graded in a manner generally similar to the grading of the interfaces in the bottom mirror 33. The doping levels are $1\times10^{18}cm^{-3}$ in uniform regions and $5\times10^{18}cm^{-3}$ in graded regions.

The phase matching layer 47, which is GaAs, compensates for phase delays that result from finite penetration of the optical field into the Au layer.

The Au layer 49 is about 2000 Å thick and is fabricated, after MBE growth of the underlying structure, as follows. First a 2000 Å layer of Au is deposited on the GaAs phase matching layer 47. Then a thick (more than 10 μm) Au button is plated on top to serve as a mask for proton isolation. The wafer is then proton implanted. Crystal structure damage that results from the proton implantation provides for current confinement and therefore gain guiding. Then another thick Au button 53 with a diameter of about 300 μm is plated on top. This button 53 is used for solder/die attachment of the completed device to a heat sink. The wafer is then lapped and polished to a diameter of 125 μm and an annular electrode 55 is patterned on the bottom. A quarter-wave anti-reflection coating 57 of $SiO_2$ (silicon dioxide) is deposited in the open region of the electrode 55.

An optical communication system embodying the principles of the invention was constructed using a relatively large-area SEL with a 25 μm opening coupled to an optical fiber. A physical discontinuity was deliberately introduced into the fiber; this discontinuity was a gap of several millimeters. The gap was adjustable to cause between 3 dB and 16 dB of loss. The length of the fiber between the SEL and the gap was 16 meters; this portion of the fiber was agitated with a shaker to simulate the effect of fiber movement. The bit err r rate ("BER") was measured for gaps of various widths; the measured BERs were less than $10^{31\ 11}$ for losses up to 10 dB.

In the tests described herein, a wavelength of about 970 nanometers ("nm") was used. It will be apparent that the principles of the invention are equally applicable to devices that are operated at other wavelengths, and that the physical dimensions will change accordingly.

In another test the performance of the large-area SEL was compared with that of a smaller SEL having a 12 μm opening. The threshold currents were about 6.5 milliamps (mA) for the large SEL and 4.2 mA for the smaller. The threshold voltages were 2.7 and 4.5 volts, respectively. The output power at twice the threshold current was 3.6 milliwatts (mW) for the larger SEL and 2.8 mW for the smaller. The emission wavelength was about 970 nm.

The SELs were modulated directly by a 1 gigabit-per-second, non-return-to-zero ("NRZ") signal at a maximum of 2 volt amplitude and with a $2^{15}-1$ pseudorandom bit sequence through a bias-T. The bias levels were several times the respective threshold currents. The SELs were directly coupled into 50/125 graded index multimode fiber. The length of the fiber between the SEL and the gap was 16 meters, and the gap was adjusted for a 10 dB loss. An optical attenuator was inserted between the gap and the receiver to keep the optical power incident on the receiver at 6 dB above the receiver sensitivity.

The receiver was a Hewlett-Packard model 83442A receiver modified for multimode use with a 60 μm InGaAs detector and a multimode FC/PC input connector. The receiver had a −3 dB bandwidth of 0.9 GHz. The AC-coupled receiver output was amplified to 2.0 volts before detection. The sensitivity of the receiver was −23 dBm for a receiver noise-limited BER of $10^{-9}$.

In this test configuration, the 25 μm SEL was operated for 16 hours without an error, resulting in a BER of less than $10^{-13}$. In other tests, the length of the fiber between the SEL and the gap (the gap was adjusted to a 10 dB loss) was varied between six and 406 meters and in every such instance the BER was less that $10^{-11}$. The 12 μm SEL was also able to achieve a BER of less than $10^{-11}$ with the gap adjusted to about a 4 dB loss.

A strongly-driven SEL with a relatively large surface area ("large surface area" means a surface opening larger than about eight μm) will operate in multiple, high-order transverse modes that are at slightly different wavelengths. As the size of the opening increases, so does the maximum number of transverse modes that can be obtained. Thus, an SEL with a 25 μm opening can be operated in significantly more transverse modes than an SEL with a 12 μm opening.

As the number of transverse modes increases, the optical bandwidth of the light produced by the laser also increases and the coherence of the light decreases. Speckle visibility measurements have shown that the speckle visibility from a large-area SEL is smaller than that of smaller SELs.

Despite operating in multiple transverse modes, the large-area SEL operates in a stable, single longitudinal mode. Longitudinal mode partition noise, which results from multiple longitudinal modes, is therefore not a significant problem with large-area SELs.

In one test, a 25 μm SEL was found to be operating in at least six distinct transverse modes at a drive current of 2.3 times the threshold current. The spectral width was $\Delta\lambda=0.75$ nm. When the drive current was reduced sufficiently to cause the laser to go into single mode operation, the spectral width was $\Delta\lambda<0.08$ nm; this measurement was limited by the resolution of the optical spectrum analyzer that was used for the test. In contrast, a 12 μm SEL was found to be operating in

single mode at a drive current 1.5 times the threshold and in two transverse modes at a drive current 2.5 times the threshold.

From the foregoing it will be apparent that an ptical communication system according to the invention is capable of carrying digital data at rates up to and exceeding 1.5 gigabits per second with very low bit error rates. The invention also offers the advantages, such as easy alignment, simple packaging and low cost, that are associated with systems using multimode optical media. In addition, SELs are expected to be easier and less expensive to manufacture than other kinds of lasers.

Although a specific embodiment of the invention has been described and illustrated, the invention is not to be limited to the specific forms or arrangements of parts so described and illustrated, and various modifications and changes can be made without departing from the scope and spirit of the invention. Within the scope of the appended claims, therefore, the invention may be practiced otherwise than as specifically described and illustrated.

We claim:

1. An optical communication network comprising:

a vertical-cavity, surface-emitting semiconductor laser structure having an aperture larger than eight micrometers through which an optical signal may be emitted;

a power supply that provides a bias current to drive the laser into a multiple transverse mode of Operation in which the laser is responsive to a signal carrying data to provide an optical signal modulated with the data and to emit the optical signal through the aperture; and

a multimode Optical medium optically coupled to the laser to carry the optical signal from the laser to a remotely-located receiver.

2. A network as in claim 1 and further comprising a receiver, optically coupled to the optical medium, that receives the modulated optical signal and recovers the data therefrom.

3. A network as in claim 1 wherein the multiple transverse mode of operation comprises more than two distinct transverse modes.

4. A network as in claim 1 wherein the multiple transverse mode of operation comprises multiple filamentation.

5. A network as in claim 1 wherein the multi-mode optical medium comprises an optical fiber.

6. A network as in claim 1 wherein the multi-mode optical medium comprises an optical waveguide.

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**See image for Certificate of Correction**

TITLE: Integrated wavelength-select transmitter

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Detailed Description Text - DETX (4):

As shown in FIG. 1, the laser head assembly 12 comprises a laser diode 20 for generating an optical beam of a known light wavelength, and a pair of aspherical optical lenses 22,24 for focusing and collimating the optical beam. The first aspheric lens 22 collects and focuses the light, creating a magnified image of the source at its back focal plane. The second aspheric lens 24 collimates the light, i.e., converts diverging light rays to parallel. An optical isolator 26 is disposed between the two lenses 22,24 to prevent any light reflected at some point further down the optical link from propagating back to the laser diode 20. For example, any light reflected by connectors or splices in the communication link will propagate down the optical fiber 28 back to the laser diode 20. The reflected power is absorbed or diverted by the optical isolator 26. It should be noted that the isolator can be placed at other points in the optical system, for example, between the second lens 24 and GRIN lens 14. The position in the preferred embodiment allows the isolator to be of small diameter. Also note that other types of lenses are possible, such as spherical. The aspheric lenses are chosen because of their ability to collect the widely divergent light from laser diodes, and focus and collimate it, with a minimum of aberration and lost optical power.

→ Cls 11-12

Other Reference Publication - OREF (1):

"Properties of Loss-Coupled Distributed Feedback Laser Arrays for Wavelength Division Multiplexing Systems", by Stefan Hansmann, et al., Journal of Lightwave Technology, vol. 15, No. 7 (Jul. 1997).

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# (12) United States Patent
Ball et al.

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(54) INTEGRATED WAVELENGTH-SELECT TRANSMITTER

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(52) **U.S. Cl.** ........................................................ **385/14**
(58) **Field of Search** ............................... 385/11-15, 32, 385/88-90, 147

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(57) **ABSTRACT**

An integrated optical transmitter for use in an optical system has an optical head assembly with an optical beam generator for providing an optical beam and a lens assembly collecting the optical beam and generating therefrom a formed optical beam. Interface optics receives the formed optical beam and provides optical coupling so as to minimize insertion loss to the optical beam. Also included is an optical modulator for receiving the optical beam from the interface optics and for providing a modulated optical beam in response to received modulation signals. The optical modulator is coupled to the interface optics to be in a fixed relationship therewith.

**24 Claims, 10 Drawing Sheets**